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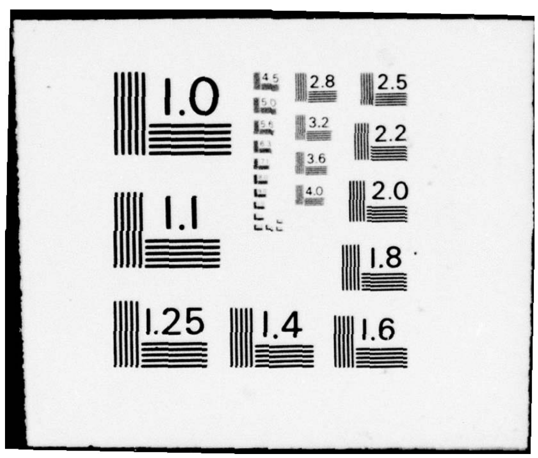
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Document Number 68-1238-C

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SUMMARY REPORT

COMPUTER-AIDED DETECTION (U)

ADA032758

002517

by

Hugh A. Reeder and H. D. Record

GROUP - 4
DOWNGRADED AT 3 YEAR INTERVALS:
DECLASSIFIED AFTER 12 YEARS.

Submitted to

Commander,
Naval Ship Systems Command
Department of the Navy
Washington, D. C. 20360
Attn: Mr. Joe Manseau, Code 00V1

19 November 1968

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(9) SUMMARY REPORT.

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Approved:

J. J. Dow

J. J. Dow
Group Leader, Signal Physics

Submitted:

Hugh A. Reeder

Hugh A. Reeder
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ABSTRACT

A technique has been developed to accomplish computer-aided detection and classification of active sonar signals. The technique is based on the theory of sequential hypothesis testing and allows a digital computer to reduce the volume of input data, perform ping-to-ping integration, and present the operator with a meaningful display at a reduced clutter rate compared to typical operational displays. The necessary logical and arithmetic operations are simple and allow real-time implementation of the technique on a modest state-of-the art computer. Detailed expressions are derived which describe the relationships between computer loading and application of the computer aided technique. A method of adaptively varying the input threshold is discussed and is shown to significantly reduce computer requirements without degrading performance appreciably. A comparison of simulated displays driven with a conventional signal processor and the computer-aided technique shows that the computer-aided technique provides consistently brighter target tracks than the conventional processor with equal clutter densities.

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1. INTRODUCTION

Most modern active sonars are equipped with a signal processing system which performs optimal processing on a single ping basis. However, these sonars present to the operator large quantities of data to be examined for possible targets. In order to detect a weak target return, the display thresholds must be set such that clutter is significant. Most sonar displays allow visual ping-to-ping integration through display of more than one ping history. This increases the probability of detection over a single ping display, but an operator must be alerted in order to achieve the best possible results. This alerted condition is difficult to maintain on long searches with few targets; so, the potential gain is limited by the performance of the operator.

Initial efforts under this study contract were directed toward an investigation of methods for utilizing digital computers to assist the operator in the detection function. A procedure based on sequential hypothesis testing was found to offer promise, and a computational algorithm was developed. The algorithm, subsequently identified as the sequential likelihood ratio (SLR) processor, is described in Ref. 1, together with some preliminary numerical results on the detection and tracking of simulated targets. A brief description of the basic algorithm is given in Appendix A of this report. The highlights of the procedure are:

1. The computer-aided technique automatically examines data from the sonar signal processor, reduces the volume of data, performs ping-to-ping integration, and by making simple decisions provides the sonar operator with a meaningful display.

2. The computer algorithm is based on a statistical decision procedure known as sequential hypothesis testing or sequential likelihood ratio (SLR) processing.

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3. The basic SLR algorithm is not dependent on a particular sonar system; rather, it is applicable to any one of a large class of active sonar systems.

4. The procedures used are well-founded mathematically, rather than being empirical, and can be shown to be optimum from the standpoint of statistical decision theory.

5. The necessary logical and arithmetic calculations are simple. This will allow real-time implementation on a reasonably modest state-of-the-art digital computer. The only restricting requirements are those of data storage capacity and speed of operation.

6. In the basic decision process there is no fundamental limit on the number of echo cycles which can be considered for ping-to-ping integration; as much of the available data is used as is necessary to make a target/non-target decision.

Results reported in Ref. 1 indicated the SLR processor to be a promising approach to computer-aided detection. At this point attention was directed to the question of the feasibility of implementing the SLR processor on a shipboard computer. Reference 2 describes an analysis of computer requirements (storage and execution time) necessary for implementation of the technique. This analysis permits an estimation of the computer requirements for a given set of sonar and SLR processor parameters. A brief description of the analysis is given in Appendix B. The analysis indicated that the SLR processor could be implemented on reasonably modest state-of-the-art digital computers. However, it was concluded that a further reduction in computer requirements was desirable in order to permit a greater range of data reduction tasks to be performed in the computer and to make the SLR technique practical for a wider range of computers.

Subsequent investigations with the SLR technique have included methods for reducing computer requirements, specifically

by limiting the amount of data which enters the SLR processor, and a performance evaluation of the SLR processor. This evaluation was conducted by means of a side by side comparison of simulated displays driven in one case by a typical sonar processor (replica correlator) and in the second case by a replica correlator augmented by an SLR processor. These investigations are described in Sections 3 and 4 of this report.

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2. BACKGROUND

2.1 GENERAL DESCRIPTION OF THE SLR PROCESS

A method of automatically achieving ping-to-ping integration on sonar data has been developed. This method utilizes a digital computer to examine the data from the sonar signal processor, reduce the volume of data, perform ping-to-ping integration, make simple decisions, and provide the operator with a meaningful display. The method is based upon the statistical decision procedure known as sequential hypothesis testing, or sequential likelihood ratio processing.

The SLR process is applied to data emerging from the output of the sonar signal processor, so that full advantage can be taken of the signal processing gains of the existing system. In the SLR process, a sample data point from the sonar signal processor's output which exceeds a preliminary threshold is transformed by a function dependent on the output statistics of the sonar processor to form an approximation to the logarithm of the likelihood ratio of this sample. Two thresholds are then utilized to continue processing the possible return. There is an upper threshold above which the log likelihood ratio is accepted as a possible target and is displayed as a mark proportional to its intensity. The log likelihood ratio is also stored in the computer along with other information such as the range and bearing for which this particular ratio is valid. The other threshold is a lower threshold below which the log likelihood ratio is considered noise alone and is rejected. If the log likelihood ratio is between the two thresholds, then it is retained in computer storage.

On the next ping, as output data and new log likelihood ratios are formed the computer links new data to old stored data. This is done on the basis of dynamic constraints on target motion in range and bearing. That is, linkages are formed from ping to ping by linking data which is within the maximum bearing and range

limits defined by maximum target motion within one ping period. If such a linkage is found, that is, if a peak from the present ping is within the search volume defined for the stored peak, the joint likelihood ratio of the two peaks is formed. This joint likelihood ratio is then compared to the two thresholds described above, and is either stored and displayed, retained in storage alone, or rejected.

2.2 PRELIMINARY DESIGN CONSIDERATIONS

The SLR processor may be adapted to operate in conjunction with any active sonar system now in operation. Knowledge of certain characteristics of the particular sonar system is necessary for this adaptation. By displaying the output of the SLR processor in the conventional fashion, that is, by displaying several ping histories, the operator can perform additional ping-to-ping integration with a reduction in display clutter rate, based on equal probabilities of detection for the SLR and non-SLR-driven displays.

Ping-to-ping integration of weak tracks below the display threshold is left to the computer until a decision is reached to display or reject the track. The rejection threshold is set such that the probability of rejecting an actual target track is very small. This leaves the computer to perform the tedious job of reducing clutter.

The transformation of the signal processor output to a log likelihood ratio is achieved through the use of a linear approximation. This transformation depends on an average design signal-to-noise ratio (S/N), as well as the processor output statistics for this S/N. The SLR hypothesis testing procedure is optimal for this design S/N, and is degraded only slightly for target tracks at higher S/N's. For tracks having an S/N below the design value, departure from optimum performance is slight initially with decreasing S/N, then greater, with a sharp cutoff in performance at about 4 to 6 dB below the design S/N. Tracks with

an average S/N below this point will not integrate up to the display threshold.

It is desirable to have the design S/N low, since this increases the probability that a target with a low S/N will be detected. However, lowering the design S/N will make it more difficult for the SLR processor to reject background noise since it will appear to be closer to the hypothesized target S/N. It is therefore necessary to keep each suspected track in the computer longer. This, in turn, increases the computer storage requirements and the time required to consider all possible linkages. Thus it is necessary to place a lower limit on the design S/N in order not to exceed the computer's capabilities.

The search volume within which possible track linkages can be made is another important parameter. It is possible to vary this search volume, and consequently limit the number of log likelihood ratios within each ping cycle which can be linked with an established track. It is also possible to limit the number of linkages to those resulting in the N largest log likelihood ratios within a given search volume. In general, the more stringent the limits, the faster the decision, target or non-target, will be made. However, too severe limits will limit possible linkages with the track of a maneuvering target. This parameter is thus dependent also upon the motion of possible targets in a particular operating area.

The selectivity of the SLR process also can be used to pick targets to be subjected to further classification procedures, depending upon available computer time and capacity. The exact classification procedures which can be implemented will depend upon the sonar system and the pulse form transmitted. In general, the ability to implement this procedure and other related operations will depend on both the computer available on board ship and the particular sonar system.

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3. ADAPTIVE THRESHOLDING TO LIMIT SLR COMPUTER LOADING

3.1 BACKGROUND

The primary obstacle to the implementation of the SLR processor is, in many cases, the availability of a shipboard digital computer with a large data storage capacity. Consequently, it is desirable to limit the data storage requirements of the SLR processor without significantly degrading the processor's capability to detect targets. The input threshold of the Preliminary Data Reduction section (see Appendix A) controls all data entering the computer and can reject an input sample before computer execution time is used to consider the sample further. Consequently, it is logical to consider this preliminary threshold as a tool with which computer loading can be controlled. This section of this report deals with a method which has been used successfully to reduce computer loading without significantly degrading the SLR processor performance. The effects of preliminary threshold variation upon performance are discussed in detail.

3.2 THE ADAPTIVE PRELIMINARY THRESHOLD

The purpose of the preliminary threshold described above is to reject small-amplitude samples which are almost certainly noise samples. Input samples which exceed this threshold may be rejected by the SLR process but require valuable computer time for this rejection. The level of the preliminary threshold also has a very significant effect on the necessary data storage requirements. A slight increase in the preliminary threshold can cause a large number of noise peaks to be rejected, with relatively few signal-plus-noise samples being rejected, for a reasonable target S/N.

There are several alternatives available which can limit the storage requirements. The preliminary threshold can be raised by a set amount, the computer can be instructed to reject all

input samples once a pre-assigned number of status units has been stored, or, the preliminary threshold can be varied according to the rate at which the data storage area fills. The last approach is more attractive, since, on the average, fewer signal peaks will be rejected; and the processor can accept data from the entire range of interest. This approach implies varying the input threshold to adapt the number of input samples accepted to the average number of status units expected to have accumulated at some point in time within the present ping cycle. This procedure is the one adopted here.

The initial step in this form of adaptive thresholding is to calculate N_{max}, the average number of status units which can be allowed to accumulate within one echo cycle. By arbitrarily defining time zero as the instant in time within each echo cycle when useful information enters the sonar processor, a linear function may be defined which represents the expected number of accumulated status units at any time within the current echo cycle. This point is illustrated in Fig. 1. In the method chosen, the function begins with a value of 1.0 at time t = 0, and increases linearly to a value of $(0.95) \cdot (N_{max})$ at time $t = \tau_e$, the end of the echo cycle. The value $(0.95) \cdot (N_{max})$ is chosen to prevent upward variations in the average number of status units acquired from exceeding N_{max}.

During the execution of the SLR process, the actual number of accumulated status units is compared with the expected number of status units at designated points in time. If the two quantities differ by more than a specified amount, then the present value of the preliminary threshold is varied properly by a factor dependent upon the square of the difference between the actual and expected numbers divided by the expected number. This technique allows automatic rapid adjustment of the preliminary threshold whenever the actual number of accumulated status units differs from the expected number by an expected amount. The

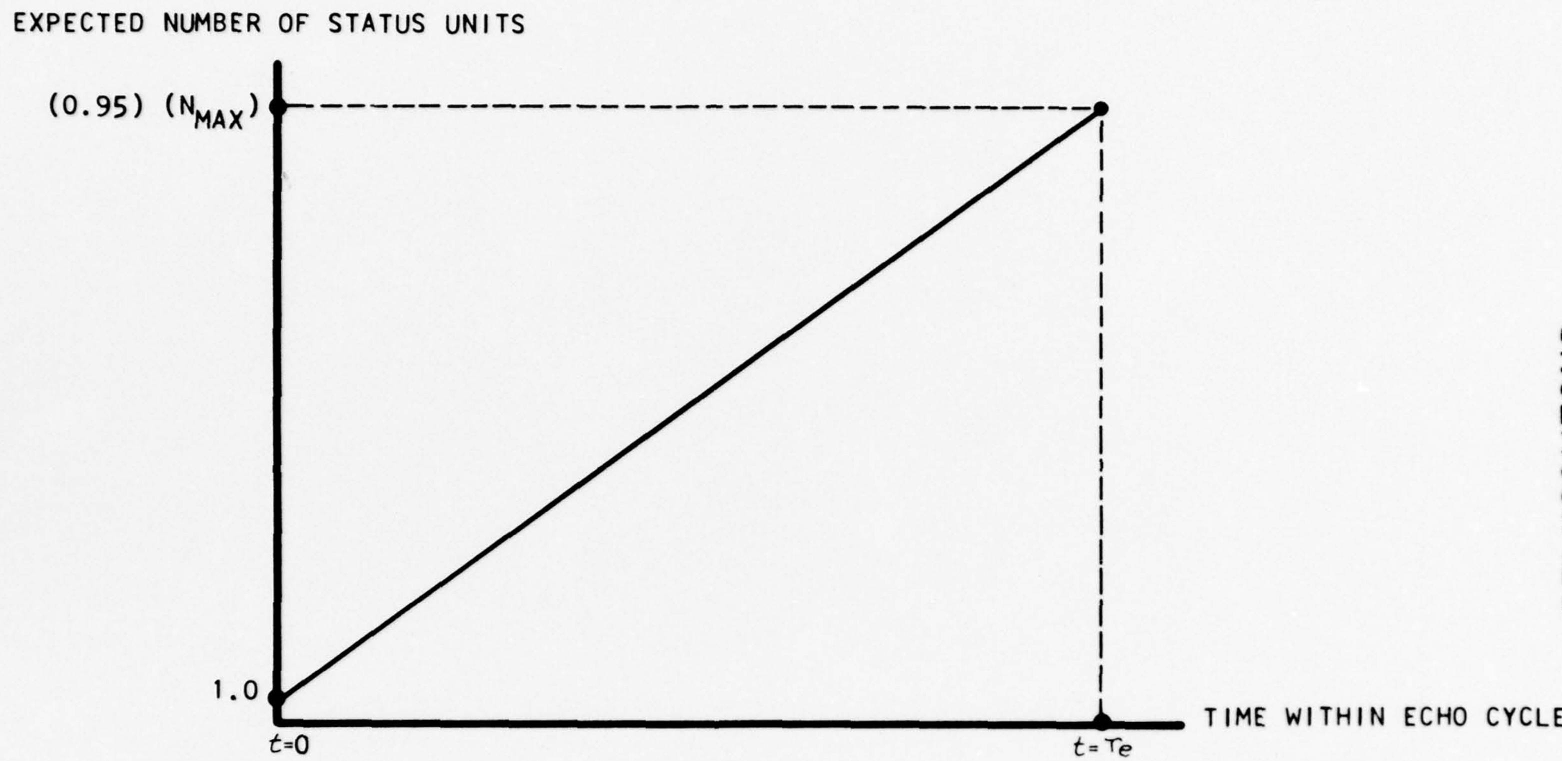

FIG. 1 EXPECTED NUMBER OF STATUS UNITS AS A FUNCTION OF TIME WITHIN A SINGLE ECHO CYCLE.

implementation described here has performed quite well in controlling computer requirements without significantly decreasing the SLR processor's detection capability. The effects of preliminary threshold variation upon the probability of detection and the average sample number will now be discussed.

3.3 EFFECTS OF PRELIMINARY THRESHOLD VARIATION

(U) In order to determine the effects of preliminary threshold variation on the probability of detection and the average sample number, a large number of echo cycles were simulated using the UNIVAC 1108 computer. The data were generated using the statistics of the envelope of noise and signal-plus-noise at the output of a replica correlator corresponding to an FM slide at the input. The statistics used for noise alone were Rayleigh and were Rayleigh-Rice for signal-plus-noise.

(C) The design S/N of the SLR processor used was 13.7 dB at the output of the sonar processor, equivalent to -8.0 dB at the sonar processor input. Several hundred target tracks at each of several S/N's were simulated and processed by the SLR processor using several preliminary thresholds. The number of samples necessary to reach a decision for each track was tabulated. From this information, the probability of detection and the average number of samples required for a decision on the target track were calculated as a function of S/N for several preliminary thresholds.

(U) Four values of the preliminary threshold were of interest. With σ_n defined as the standard deviation of the output waveform of the sonar signal processor with noise alone input and μ_n the mean for noise alone input, the four thresholds were the following:

1. $\mu_n - \sigma_n$
2. $\mu_n + \sigma_n$
3. $\mu_n + 2\sigma_n$
4. $\mu_n + 3\sigma_n$.

Threshold 1 allows the greatest number of noise and signal-plus-noise samples to pass, consequently the results of the Threshold 1 test form a basis of comparison of the remaining three.

Using the results of the test described above, the probability of detection* versus actual S/N was calculated for each of the four preliminary thresholds. These curves are shown in Fig. 2. Note that the curves for Threshold 1 and Threshold 2 almost coincide. Hence the preliminary threshold can be raised to the higher value without degrading the SLR processor's detection capability. With Threshold 3, the degradation in detection capability becomes significant, but not crippling. However, the performance degradation caused by Threshold 4 is unacceptable.

From the results of the above test, the average number of samples required to reach a decision for a signal having passed the preliminary threshold was tabulated as a function of actual S/N at the processor input for the four preliminary thresholds. These curves are shown in Fig. 3. From these curves it can be seen that the average number of samples did not vary significantly for Thresholds 1, 2, and 3. The average number of samples was somewhat lower for Threshold 4; one explanation of this phenomenon is that once a signal-plus-noise sample is large enough to exceed Threshold 4, it has a higher probability of marking the display.

From the results of this test, it was found that the computer data storage requirements decreased rapidly as the preliminary threshold was raised. It can be concluded that if the adaptive preliminary threshold is restricted to be less than $(\mu_n + 2\sigma_n)$, then the SLR processor performance will not be significantly degraded, and that with the threshold $T = \mu_n + 2\sigma_n$, the computer requirements are a minimum with respect to performance capability. If the storage requirement still is excessive, other methods must be used to limit data storage, such as reducing the number of range resolution cells.

*Detection is said to occur when the joint log likelihood ratio for a target track exceeds the display (upper) threshold in the SLR process.

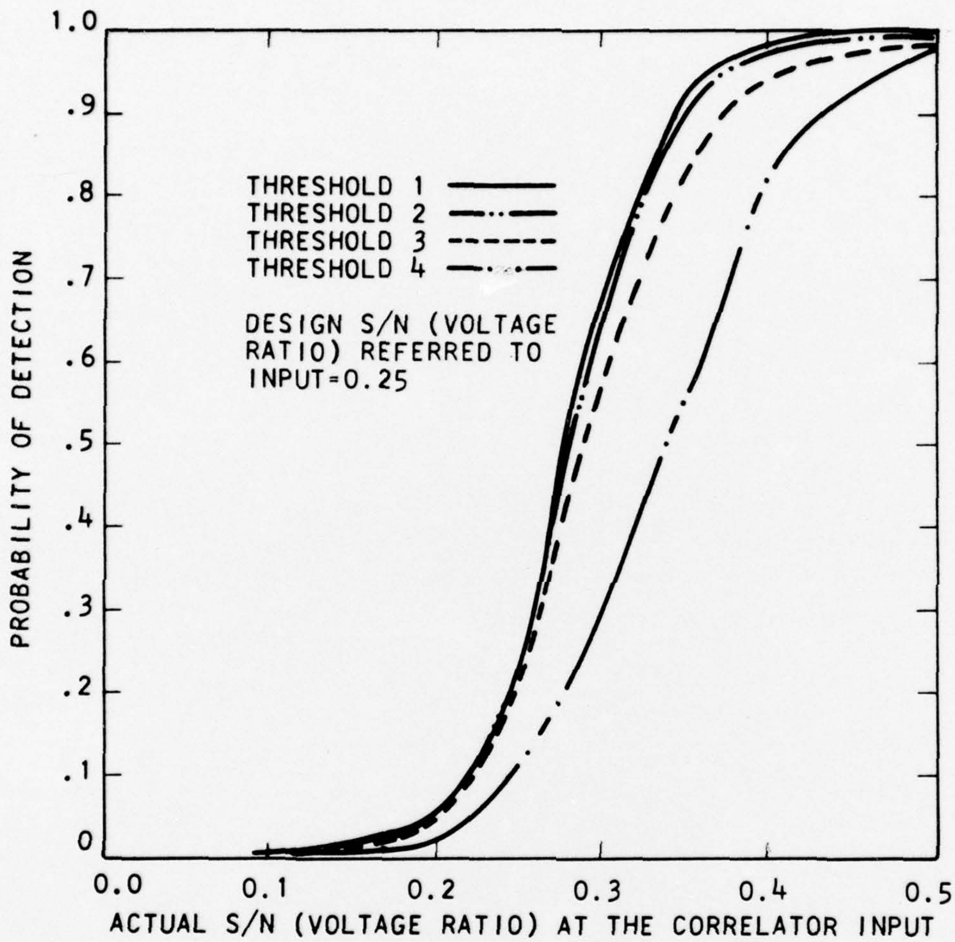

FIG. 2 PROBABILITY OF DETECTION FOR THE SLR PROCESSOR VERSUS ACTUAL S/N AT THE CORRELATOR INPUT FOR VARYING PRELIMINARY THRESHOLDS.

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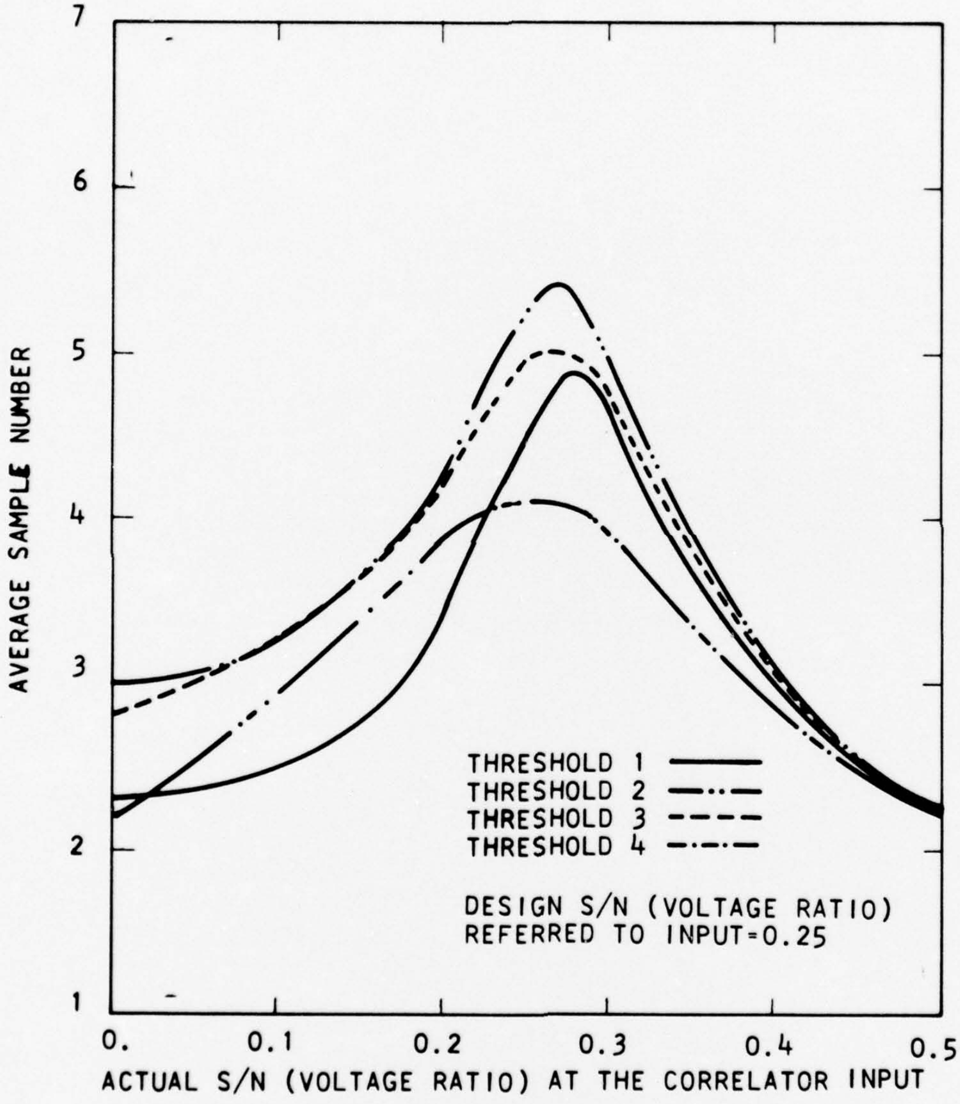

FIG. 3 AVERAGE SAMPLE NUMBER AS A FUNCTION OF ACTUAL S/N AT THE CORRELATOR INPUT

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4. COMPARISON OF SLR AND NON-SLR PROCESSING

4.1 INTRODUCTION

In order to provide a comparison between SLR and NON-SLR processing methods, a simulation was conducted using the UNIVAC 1108 computer and the TRACOR color display facility. The simulation included generation of six beams of replica correlator output. These outputs were generated for 20 pings and included a target with motion in both range and bearing. Data were generated according to the output statistics of a conventional replica correlator, and included a target closing from outside its detectable range and moving across several beams. The resulting data were recorded on digital magnetic tape for use with each type of processing system. In effect, this tape contained simulated recordings of the processed outputs of six beams of an active sonar for 20 echo cycles with a single moving target.

The recorded data were then passed through the simulated system as shown in Fig. 4. For each type of processor, SLR and NON-SLR, a statistical analysis was performed on output data for noise alone at the input to the processor. The output noise statistics (probability of exceeding threshold versus threshold) were used to set display intensity thresholds for each type of processor such that the noise clutter density would be the same on the average for each processor.

Initially a black and white display similar to the AN/SQS-26 A-scan was used for the comparison. However, on the black and white CRT, all levels of intensity* were not readily discernible. By a simple change of data format, it was possible to display the data from each processor on a color CRT. With the color display,

*Eight levels of intensity were used for the comparison.

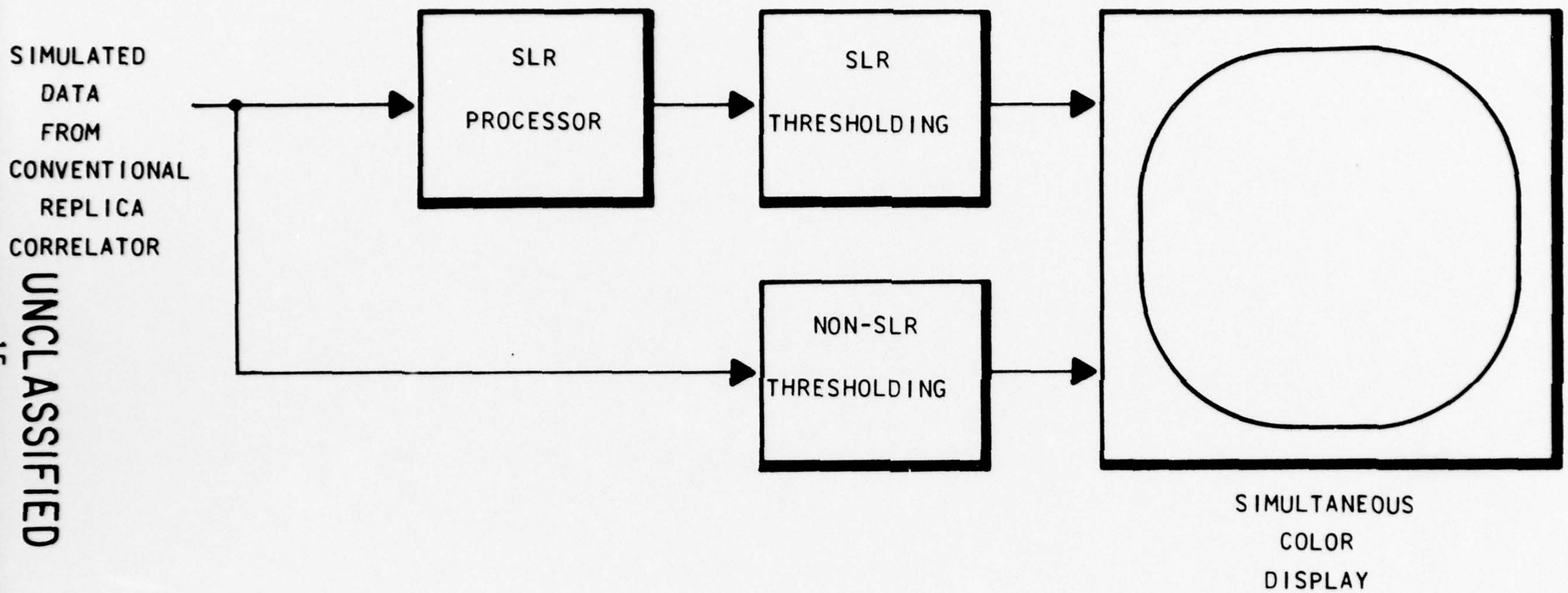

FIG. 4 BLOCK DIAGRAM OF THE SYSTEM SIMULATED FOR COMPARISON OF SLR AND NON-SLR PROCESSING METHODS.

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(U) each level of intensity was coded as a different color, so that marks of different intensities were readily discernible. The results of the color display comparison were quite favorable to the SLR processing, and are presented later in Section 4.3. The next section of this report gives a detailed description of the comparison test.

4.2 STRUCTURE OF THE COMPARISON TEST

(U) Data simulating the output of a conventional replica correlator were generated on the UNIVAC 1108 computer in the following fashion. It was assumed that the sonar signal processor was a linear replica correlator followed by an envelope detector. As previously mentioned, after envelope detection the noise-alone statistics are Rayleigh, and the statistics for signal-plus-noise are Rayleigh-Rice. A discussion of these statistics is given in Appendix B of Ref. 1.

(C) The use of Rayleigh-Rice statistics for the replica correlator output requires specification of the theoretical S/N at the correlator input. Hence, to simulate target motion the S/N was varied linearly in dB as a function of target range for each ping, as shown in Table I. For each ping of simulated data the maximum value of the envelope at the correlator output in the presence of signal-plus-noise, P_i, was recorded. Thus a single ping "S/N" was calculated for the envelope of the correlator output for each echo cycle and is given by

$$\text{single ping "S/N"} = 20 \log\left(\frac{P_i - \mu_n}{\sigma_n}\right).$$

These values are included in Table I, as are the actual S/N's at the correlator output (assuming envelope detection). The particular processor simulated here assumes a time-bandwidth product of 50. This is typical of the time-bandwidth product used in the AN/SQS-26 and was chosen as a realistic example for the comparison.

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TABLE I

S/N FOR THE COMPARISON TEST (U)

PING NUMBER	S/N AT THE CORRELATOR INPUT (dB)	S/N AT THE CORRELATOR OUTPUT (dB) (ASSUMING ENVELOPE DETECTION)	SINGLE PING "S/N" (dB)
7	-10.3	9.6	13.4
8	-10.1	9.9	11.5
9	- 9.9	10.1	7.1
10	- 9.7	10.4	11.7
11	- 9.5	10.7	12.6
12	- 9.3	11.0	13.4
13	- 9.1	11.3	11.2
14	- 8.9	11.6	15.7
15	- 8.7	11.8	14.3
16	- 8.5	12.1	5.1
17	- 8.3	12.4	16.6
18	- 8.1	12.6	13.5
19	- 7.9	12.9	12.1
20	- 7.7	13.2	3.7

(U) In Section 4.3.2, Table III lists target position and marking intensity for each echo cycle presented in this report. These marking intensities correspond to the single ping "S/N's" listed in Table I. It is felt that in the absence of a large statistical average, the correspondence between the single ping "S/N" and the marking intensity for each echo cycle illustrates the ability of the SLR processor to propagate a strong target track in spite of variations in the processor output.

(C) For each test run, twenty pings of data were generated; the data represented a range segment of 10,000 yards, with a zone-start range of 20,000 yards, and covered six ten-degree beams. Six beams were used so that the two processors' outputs could be displayed simultaneously on the CRT. The data from the six beams of the NON-SLR processor were input to the SLR processor, both were individually thresholded, and both were displayed.

(U) The design S/N of the SLR processor was set for a S/N of 12 dB at the correlator output. The criterion for this choice is explained in Appendix B of this report. The initial threshold in the Preliminary Data Reduction section was set at $\mu_n + \sigma_n$, the second threshold value described in Section 3.3. The adaptive threshold was not used; instead all necessary data storage was available to the SLR processor.

(U) In order that some control would be possible during the comparison, a statistical analysis was performed on portions of each set of processor output data resulting from noise alone input to the correlator. Thus, empirical curves of the probability of a noise sample crossing the threshold versus the threshold were obtained for each processor output. Using these curves, threshold values were chosen for each level of intensity for each processor such that there were equal probabilities of a noise mark of the same intensity for each processor output. The choice of these thresholds was based on an attempt to provide as much contrast as possible between clutter marks and target signal marks for marginal

(U) signal-to-noise ratios. Nevertheless, the comparison is objective since there are equal probabilities of noise marks for each intensity for both the NON-SLR and the SLR driven displays. The probabilities of noise exceeding the thresholds that resulted are presented in Table II.

(U) The simulated target began at ping 1 at a range of about 27,000 yards in beam 2, and closed to about 24,000 yards ending in beam 4 at ping 20. The target range rate was then about 4.5 knots closing. The results of the display comparison are explained and illustrated in detail in the next section.

4.3 RESULTS OF THE COMPARISON TEST

4.3.1 Display Format

(U) The color CRT display was divided in two sections in order that the output of each processor might be viewed simultaneously. The NON-SLR data were displayed on the left side of the screen, and the SLR data were displayed on the right side of the screen, as labeled on each of the photographs which follow in Section 4.3.2. The same data were used to generate the display for each processor, so that at all times, the target lies in the same resolution cell for each processor.

(U) The section of the color CRT used to display the simulated data was 200 independent resolution spots high, and 190 independent resolution spots wide. The range segment displayed was 10,000 yards, with the zone start range of 20,000 yards beginning with the horizontal line at the bottom of the screen, and with 30,000 yards represented by the horizontal line just under the color reference bar. Each mark on the display is one spot high and two spots wide, thus representing 200 resolution cells of 50 yards each.

(C) As previously mentioned, the BT product used here is the same as that used in the AN/SQS-26, thus for consistency it was assumed that the output bandwidth of the processor was 100 Hz. This

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TABLE II

PROBABILITIES OF NOISE MARKING AT EACH INTENSITY LEVEL

INTENSITY LEVEL	PROBABILITY OF MARKING WITH INTENSITY LEVEL I_i OR HIGHER
I_1	0.10
I_2	0.02
I_3	0.01
I_4	0.003
I_5	0.0015
I_6	0.0002
I_7	0.00007

(C) means that there are 100 independent samples per second at the simulated processor output. There are then about six independent samples which fall within each 50 yard display resolution cell. To obtain a single sample for each resolution cell, the maximum of those samples occurring within the cell is chosen. (Thus, the marking probabilities mentioned earlier include the effect of OR-Gating.)

(U) There are seven levels of marking intensity available above black, shown in the color reference bar at the top of the screen in order of increasing intensity from left to right. The average clutter rate for each level is the same for each processor. The thresholds for each processor and these clutter rates are given in Section 4.2.

(U) Six beams of each type of data are displayed, each containing a history of the four most recent ping cycles in order of occurrence from left to right within each beam. The most recent ping is labeled in the upper right corner of the screen. Between ping histories there is one column of blank spots, and between beams there are four columns of blank spots. The beams are marked with tick marks at both the top and bottom of the range scale.

4.3.2 Display of Results

(U) Fourteen color photographs, representing ping cycles 7 through 20, are presented in this section. Following the photographs, Table III describes target position and marking intensity for each ping cycle shown. As noted above, the target is in the same resolution cell for each processor.

(U) As previously stated, the clutter densities are the same for each processor, so that the primary difference which can be seen on the display is the difference in intensity of target marks. As seen in Table III the SLR processor produced target marks which were, on the average, about one level of intensity greater than the NON-SLR target marks. It can be seen from the photographs that

the SLR processor possesses the capability to propagate strong target tracks when the signal-plus-noise output in a ping cycle is small (fluctuates downward), whereas the NON-SLR processor has no such capability. This is illustrated in pings 9 and 20.

Close examination of pings 11, 12, and 13 reveals that the SLR-produced target track appears earlier than the NON-SLR track. This is a subjective point, however, and since the data presented here are in lieu of a large statistical average combined with operator tests, no attempt will be made to determine exactly the time of detection. Examination of pings 13 through 18 shows that the SLR track stands out much better than the NON-SLR track.

This can be illustrated by calculating the ratio of average track intensities for each processor. By weighting the target marks for each processor with the corresponding level of intensity, the SLR target track shows an intensity about 1.75 dB greater than the NON-SLR track. Thus, the SLR processor produces a consistently higher intensity of target marks given equal noise clutter densities for each processor.

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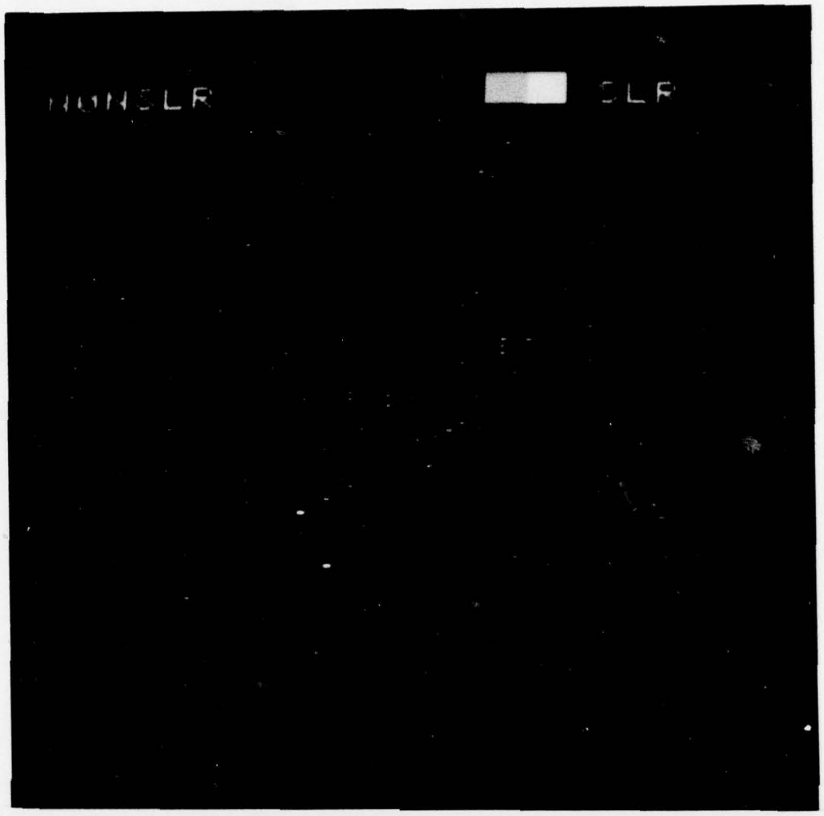

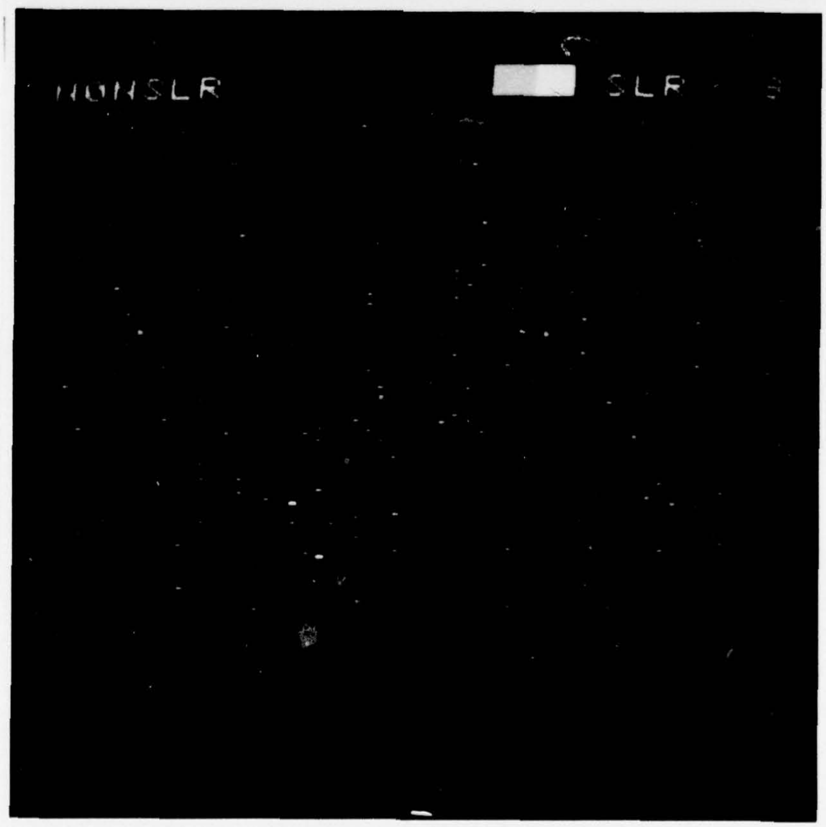

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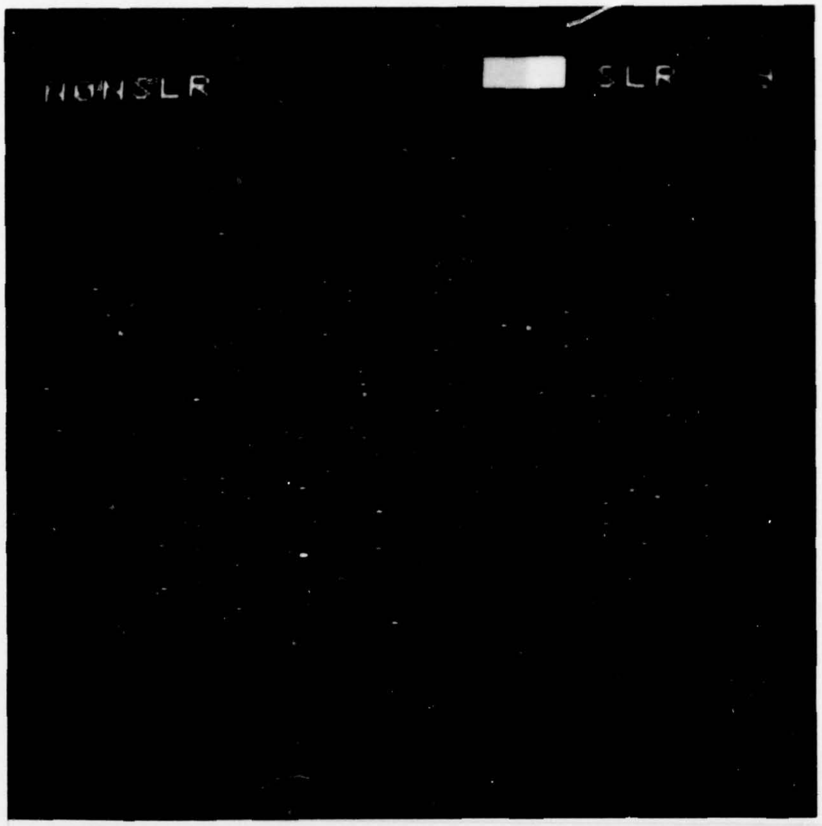
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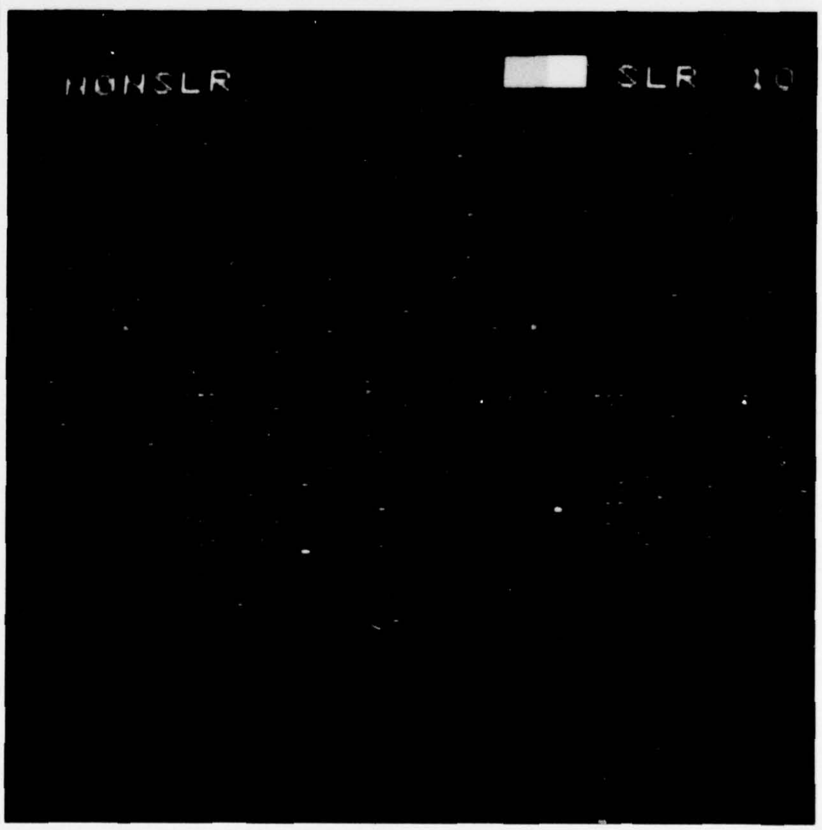
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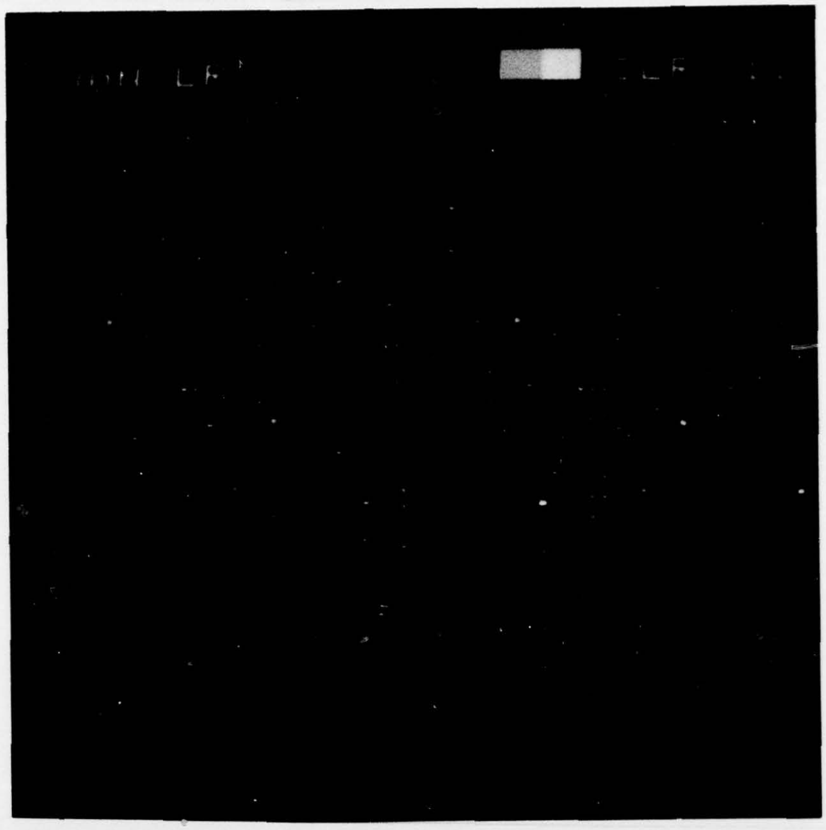

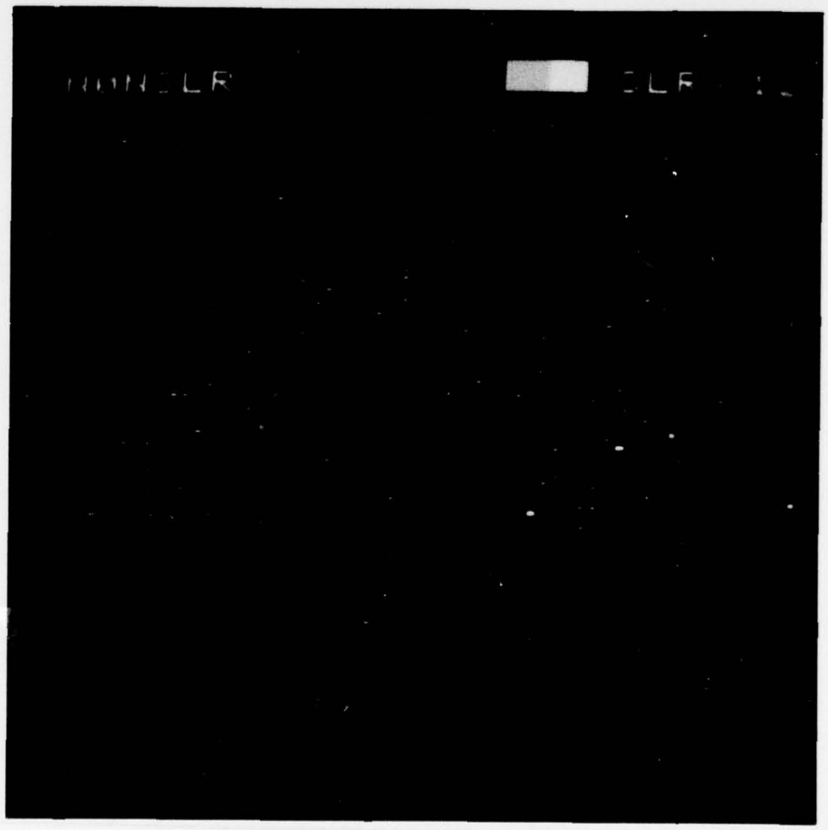

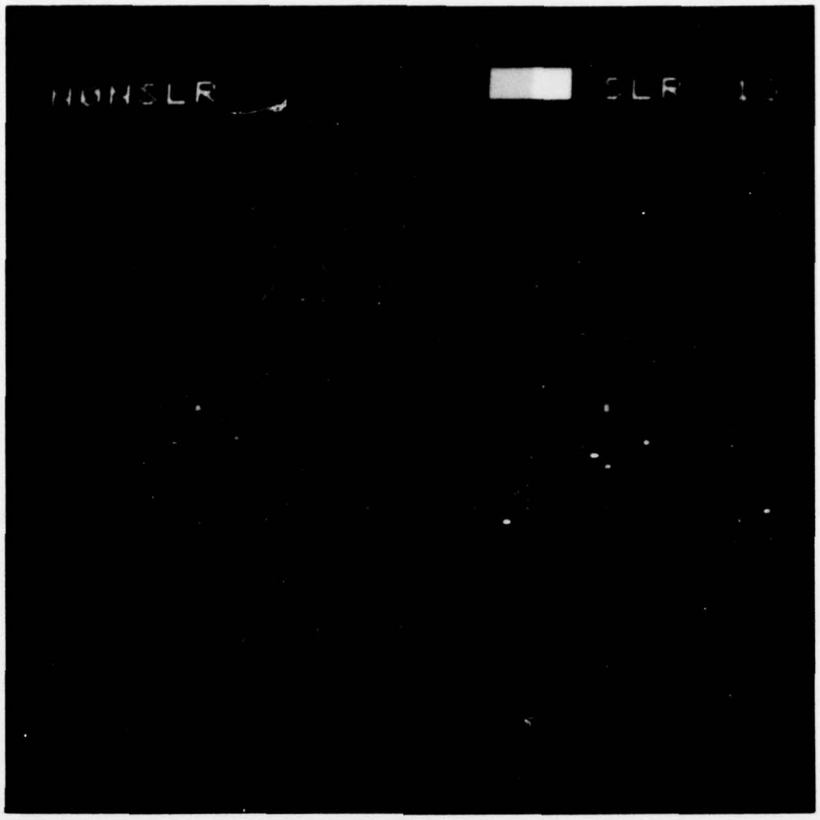
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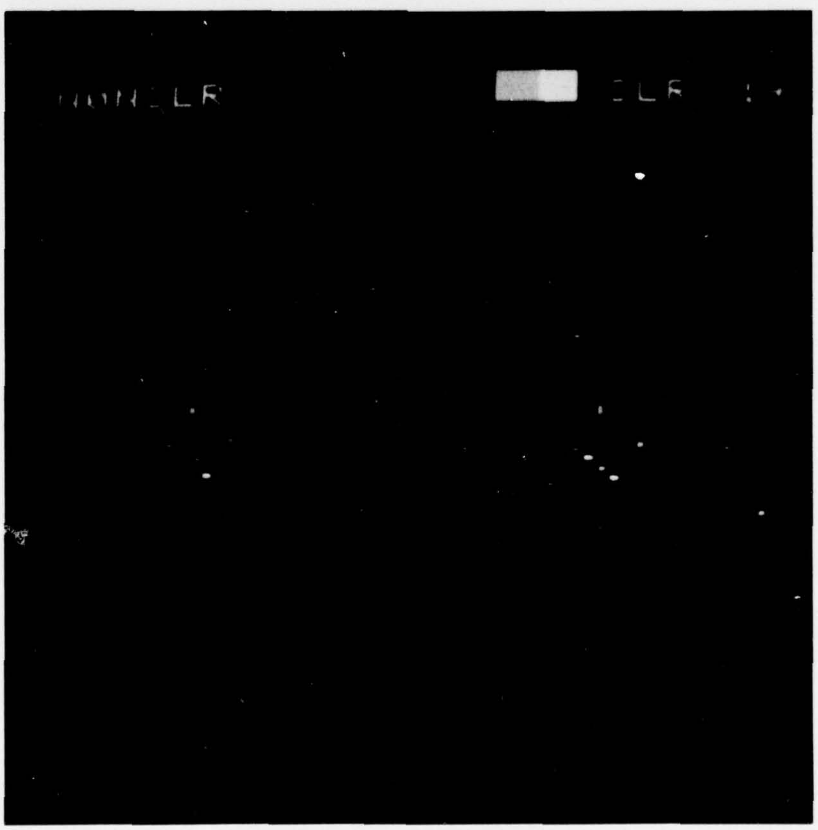
SLR


NONSLR
SLR

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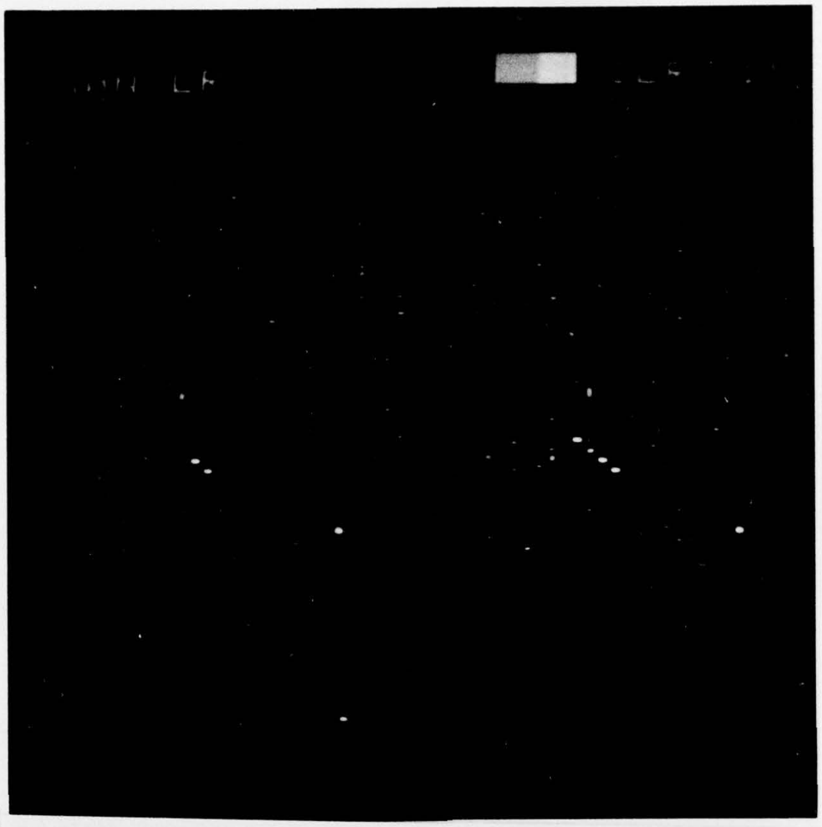

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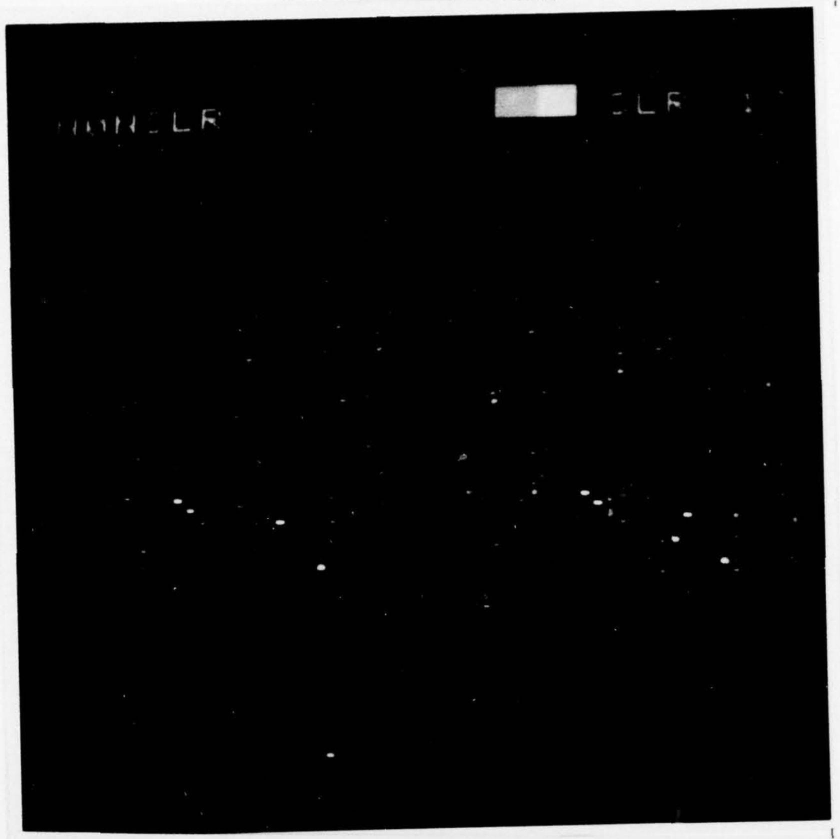

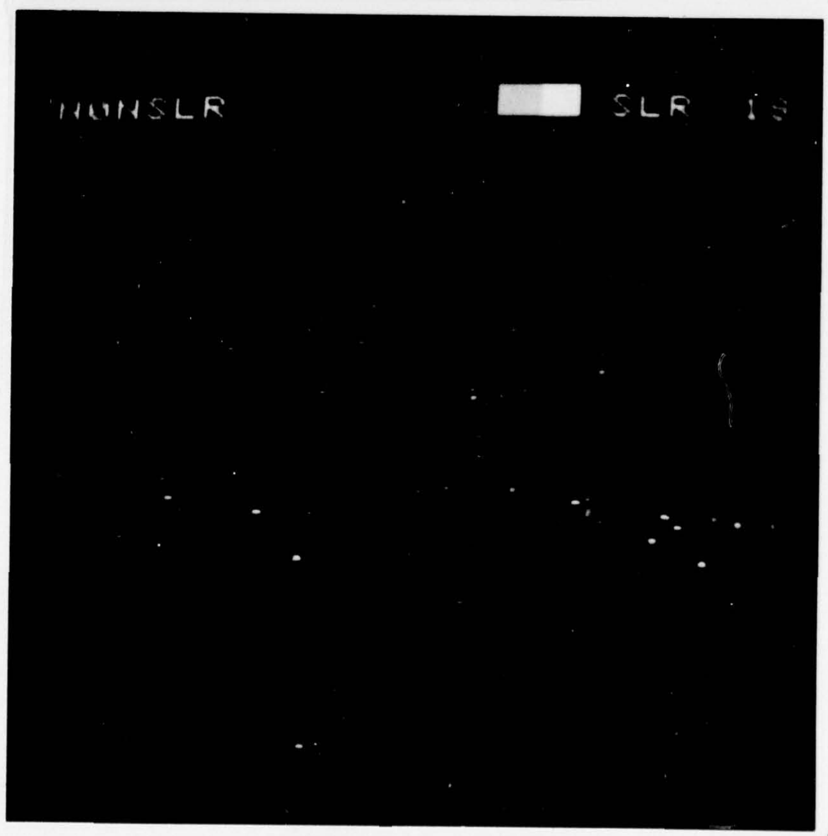

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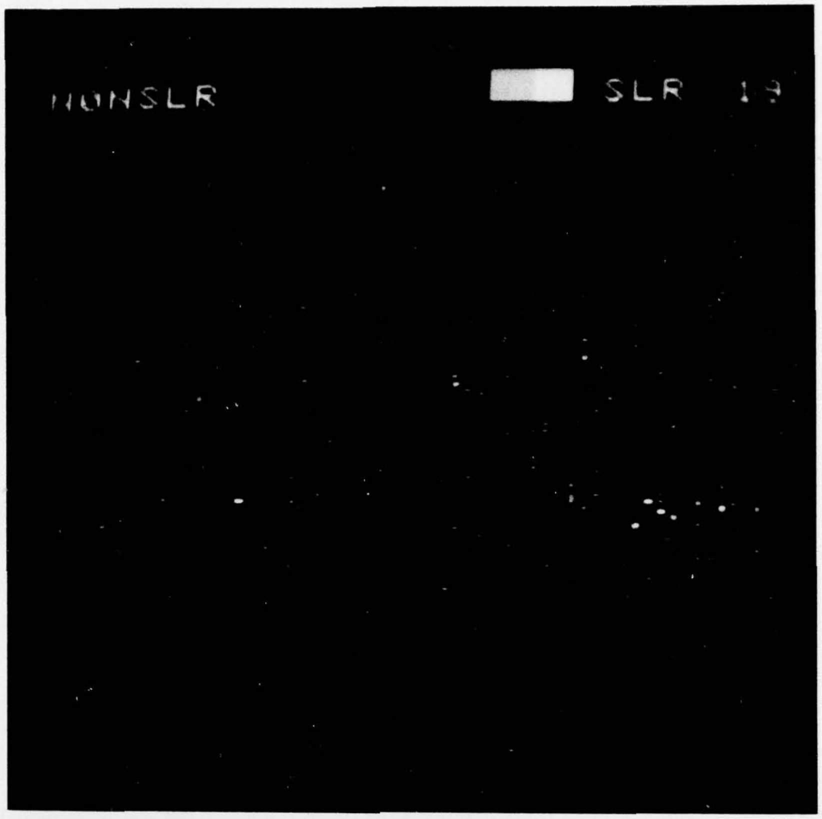
NØNSLR
SLR 19

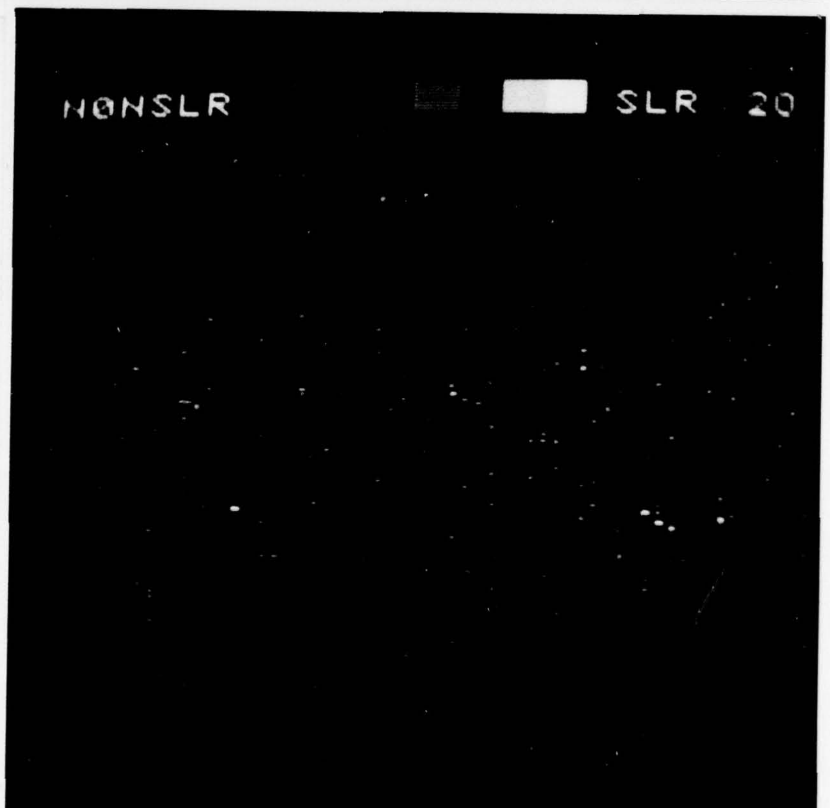
NØNSLR
SLR 20

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TABLE III

TARGET POSITION AND MARKING INTENSITY

Ping No.	Beam	Distance From Bottom Line(cm) On SLR Side	Color of NON-SLR Mark	Color of SLR Mark
7	2 & 3	5.4	Red	Red
8	3	5.2	Blue	Pink
9	3	5.0	Miss	Dark Green
10	3	4.8	Blue	Blue
11	3	4.7	Pink	Red
12	3	4.5	Red	White
13	3	4.4	Blue	Pink
14	3	4.2	White	White
15	3	4.1	Yellow	White
16	3	3.9	Blue	Blue
17	4	3.9	White	White
18	4	3.8	Red	White
19	4	3.7	Blue	Red
20	4	3.6	Miss	Dark Green

	0	1	2	3	4	5	6	7
Key:	Black	Dark Green	Light Green	Blue	Pink	Red	Yellow	White

Increasing Intensity →

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5. SUMMARY AND CONCLUSIONS

A technique has been developed to accomplish computer-aided detection in an active sonar system. The computer-aided technique is based on sequential likelihood ratio (SLR) processing. The SLR processor is designed to fit in a conventional active sonar processing system between the sonar signal processor and the output display. The SLR processor allows the automatic rejection of noise and automatic ping-to-ping integration within the computer.

The basic limitation of the SLR processor is the computer capacity necessary for its implementation. Studies have been completed which permit an estimate of the computer requirements necessary to implement the SLR process as a function of sonar and processor parameters. While implementation is feasible on a modest digital computer, further reductions in computer requirements will permit the utilization of the processor for a broader range of tasks and will permit the incorporation into the processor of certain realistic effects such as multipath structuring of target echoes. A method of adaptively varying the input data threshold as a function of the rate at which available computer storage is filled has been developed as a means to reduce these capacity requirements. This method has been shown to reduce the required computer capacity without significantly degrading the processor performance.

A comparison of displays driven with NON-SLR processing and SLR processing has been made, with photographs of an output display presented for a series of 14 ping cycles. The comparison has shown the SLR process to be uniformly superior to the optimum single-ping processor alone. The SLR processor produced target marks that were, on the average, approximately one level higher in intensity than the NON-SLR processor. When the signal level dropped within an established track, the SLR maintained the target

track; whereas the NON-SLR has no capability to propagate a track through a missed echo cycle. It should be noted that the comparison was carried out on the basis of equal clutter density at each intensity level for the two processors. Thus, the SLR processor is consistently better than the NON-SLR processor in that a target track shows up earlier, stands out better, and is more consistent with a varying signal level.

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6. RECOMMENDATIONS

6.1 INTRODUCTION

The studies presented in this report have centered on an implementation of sequential hypothesis testing as a computer-aided detection technique. The sequential likelihood ratio (SLR) processor has been simulated on TRACOR's 1108 digital computer and has been shown to be a reasonable approach to ping-to-ping processing and data reduction. This section outlines studies that should be undertaken to further improve the SLR processor. The studies fall into two main categories: (a) reducing the computer requirements of the SLR processor, thereby leading to realistic shipboard implementation, and (b) incorporating the existing body of knowledge regarding realistic target/environment features such as fluctuating target strength and structured echoes into the SLR algorithm.

6.2 REDUCING COMPUTER REQUIREMENTS

The first area recommended for study is concerned with the development and evaluation of methods of reducing the computer storage and execution time requirements necessary to implement the basic SLR algorithm. It is anticipated that this area should receive attention prior to area (b) above. In particular, three techniques should be analyzed:

(1) Rejection of multiple linkages.
(2) Updating the design signal-to-noise ratio.
(3) Use of a modified likelihood ratio.

Also, the effect of each of these modifications on display clutter rates should be determined.

Any means of reduction in computer requirements likely will constitute a departure from strictly optimum operation. Therefore, this study should be directed toward finding those means of reduction which provide (1) a reduction in data handling

requirements sufficient to permit the SLR processor to be implemented on present-day shipboard computers, and (2) a minimum departure from optimum operation for the SLR processor.

6.2.1 Rejection of Multiple Linkages

In the description of the general SLR processor as outlined in Appendix A, it is pointed out that a new single ping event may link with several multi-ping events contained in the status file, or, conversely, one status unit may link with several single ping events. This fact was brought into the calculations of computer requirements. The multiple linkage can affect computer loading significantly, especially when the design S/N is low and/or the input threshold is low. Since a strong target track with a large joint log likelihood ratio may link with a small noise peak, a false track with a respectable log likelihood ratio may result. While it is true that this track would be discarded soon, it must, nevertheless, be carried in the computer for that time. This problem can be alleviated if the number of linkages which a single ping event can make is limited.

6.2.2 Update Design S/N

This study would develop methods for determining the design signal-to-noise ratio required to achieve a specified computer loading. This problem is important from two points of view; one, assuming a particular computer is available for SLR processor implementation, the proper design S/N must be determined in order not to exceed the available storage. On the other hand, it is desirable to utilize all the available storage in order that as much information as possible be processed by the SLR processor. Results described in letter reports dated 2 February 1968 and 4 April 1968 show that increasing the design S/N decreases computer loading but increases the minimum detectable signal-to-noise ratio. Consequently, it is possible and desirable to determine the "best" design S/N as a function of available computer storage.

6.2.3 Modification of Log Likelihood Ratio

The sequential test uses a likelihood ratio based on the two probability density functions associated with the two possible outcomes. In Appendix B of Reference 1 it was found that for a case of particular interest the logarithm of the likelihood ratio can be reduced to a linear function. Once this log likelihood ratio function is found, the probabilities of detection for various signal-to-noise ratio targets are fixed. Also, the average number of pings required to reach a decision, hence the average computer requirement, is fixed.

In this study the problem would be reversed in the following sense. Instead of assigning an average noise sample the value given by the log likelihood equation, a value would be assigned in order to achieve a given average rate of rejection. That is, if a track consisted of samples with amplitudes equal to the average noise level, the log likelihood ratio would be assigned values resulting in rejection within a given average number of ping cycles. Similarly for an average sample value of a track of specified signal-to-noise ratio, a value would be assigned to achieve acceptance in a certain number of pings. These two values then determine a straight line which replaces the log likelihood ratio in the decision process.

Since the exact sequential likelihood ratio test is optimum, any variation is sub-optimum; however, the degradation may be small and the benefits, faster rejection of noise and controlled rate of detection, could outweigh the degradation.

6.2.4 Prediction of Display Clutter Rates

Since the display clutter rate is fundamental in the design of any sonar system, effort must be directed toward obtaining estimates of this quantity as a function of each of the SLR processor parameters. For each of the modified versions of the SLR processor discussed previously, clutter rates would be

predicted and compared with those obtained for the baseline processor.

6.3 INCLUSION OF TARGET AND MEDIUM EFFECT

The SLR processor ultimately should be modified to account for the target/environment effects on target strength and echo structure. In particular the likelihood ratio of the SLR Processor should be redesigned to account for the statistical variation of target echo strength which occurs from ping to ping. Also, computer methods of achieving signal recombination of some of the loss in sonar processor output signal-to-noise ratio which occurs in the presence of target and medium-induced structured echoes should be developed.

6.3.1 Fluctuating Target Strength

The present form of the likelihood ratio is based upon the assumption that the signal-to-noise ratio at the sonar input is a constant, non-random quantity. For real world environments this assumption is not correct. It should be possible to design a likelihood ratio including the effects of random ping-to-ping, signal-to-noise ratio variations. However, it will be necessary to weigh the improvement of the SLR processor against the complications involved.

The first step in attacking these problems would be to obtain the probability density function which describes the output of a correlator when noise plus fluctuating echoes are present at the processor input. This work should be based on analysis of target strength distributions such as those reported by Leiss[6]. Once the distribution of echo strength has been established, the probability density function describing the correlator output would be developed using the same theoretical approach as taken by Swerling[7,8]. Having this function will make it possible to obtain a new form of the likelihood ratio. Second, the SLR processor should be implemented using this new likelihood

ratio (or an approximation thereto) so that a performance comparison can be made between the present form of SLR processor and the generalized form.

6.3.2 Structured Echoes

It is well known that structured (multi-component) target echoes often arise at the input to the sonar due to one or a combination of medium-multipath effects, target structure, or differential Doppler shifts among several scatterers on the target. When the sonar transmitted signal possesses high resolution in range and/or Doppler (as is the case for large time-bandwidth product signals such as linear FM or pseudo-random FM transmissions), a coherent processor such as a replica correlator often resolves the echo structure and produces an effect known as energy splitting. The actual effect is that the energy in the composite input signal is resolved into its component parts at the output of the correlator. Energy splitting arises because the correlator reference is not matched to the echo structure. This is to be compared with the sort of output that would arise if the replica in the correlator could be structured exactly like the received signal. In this case (which is, of course, not attainable in reality) the energy in the received signal would appear in a single correlator output spike. Thus the problem here is to find some way to recombine a multiplicity of correlator output spikes into a single spike whose amplitude to some degree approximates the energy in the composite input signal. If this can be done, the signal-to-noise ratio with which the SLR processor operates can be increased and the intensity of target marks on the display will increase.

Various means of achieving signal recombination have been developed in the past with varying degrees of success[9,10,11]. These methods should be reviewed and the most promising method implemented as an improvement to the SLR processor.

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With the advent of modern digital computers, tedious tasks may now be left to the computer. Advanced decision theory techniques, such as the SLR process, have a definite place in the future, and should be developed for necessary applications today.

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APPENDIX A

MATHEMATICAL FORMULATION OF THE SLR PROCESSOR AND DESCRIPTION OF THE SLR COMPUTER PROCESS

A.1 HYPOTHESIS TESTING

A.1.1 The Likelihood Ratio

In this appendix, the likelihood ratio and its usefulness in statistical decision theory will be described. The fundamental problem of statistical decision theory is that of choosing one of several possible hypotheses by utilizing information gained from the measurement of some quantity. A great deal of generality can be included in defining the algorithm to optimally carry out this procedure, but a simplified approach will be taken here. For a background in statistical detection theory, the reader is referred to Helstrom[3]; and for further study in sequential analysis, the reader is referred to Wald[4].

For the case at hand, two hypotheses are available, H_o and H_1, where

H_o: the track is non-target or noise to be rejected,

and

H_1: the track is a target to be displayed.

In this analysis it is assumed that the quantity to be observed is a single numerical value. This observation quantity is the output of the optimum processor on a single ping basis, and usually consists of at least a position vector, with other measurements dependent upon the particular sonar system. If the hypothesis H_o is true, then observed values of the quantity x will be described by a known probability density function, $p_o(x)$, such as the example shown in Fig. A-1. Similarly, if the hypothesis H_1 is true, there will be a different probability density function, $p_1(x)$, which describes the quantity x, as shown in Fig. A-1. For

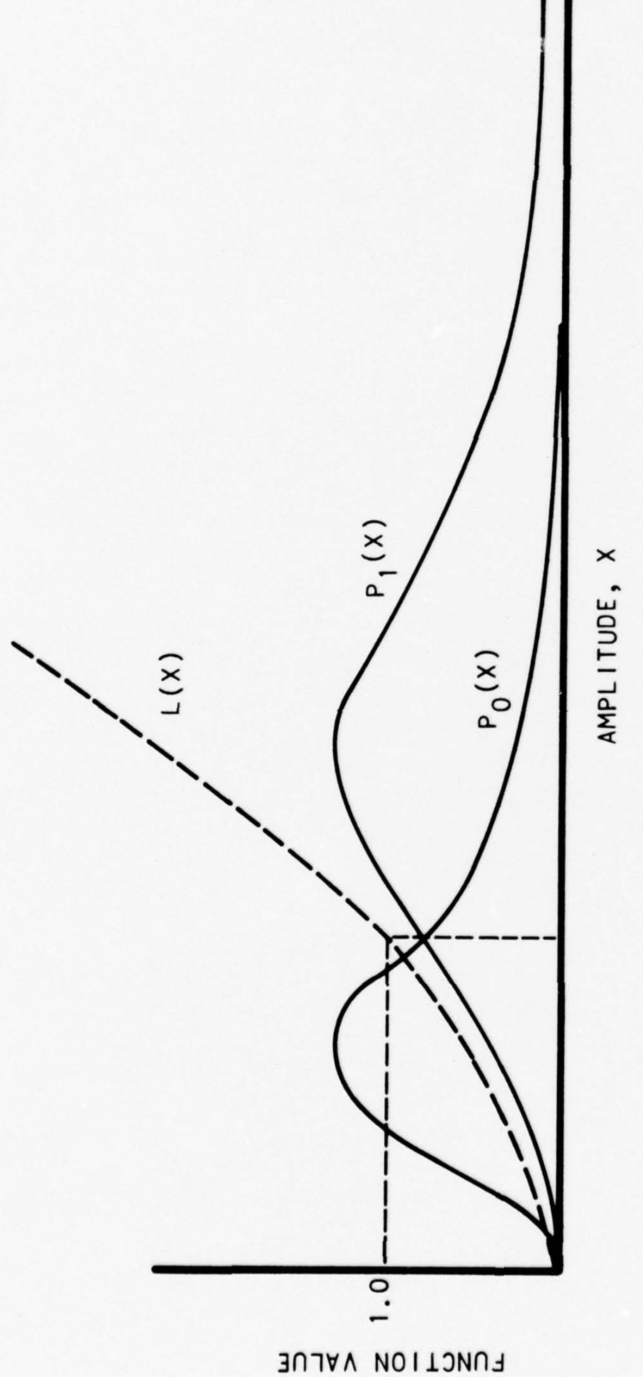

FIG. A-1 TYPICAL PROBABILITY DENSITY FUNCTIONS AND LIKELIHOOD RATIO

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10-30-68 RECORD

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this example, x can be considered as the amplitude at some point in time of the output of a signal processor, $p_o(x)$ as the probability density function describing the processor output with noise alone input to the processor, and $p_1(x)$ as the probability density function describing the processor output with signal-plus-noise input to the processor. The likelihood ratio, L(x), is then defined as

$$L(x) \triangleq \frac{p_1(x)}{p_o(x)} .$$

In many cases the likelihood ratio is a monotonically increasing function of the observation quantity x, as in this example. Here, large values of L(x) tend to imply a decision that H_1 is true, while small values of L(x) tend to imply that H_o is true. Consequently, a decision threshold can be established for L(x). There are several techniques for choosing an optimal threshold. The threshold applicable in this case must be based upon computer capacity and the false alarm or clutter rate which can be tolerated.

A.1.2 Multiple Observations

If observations of the quantity x are to be made at separate points in time, resulting in the sequence $(x_1,x_2,x_3,\text{etc.})$ then a joint likelihood ratio, $L(x_1,x_2,x_3,\ldots)$ can be defined based upon the multi-dimensional probability density functions, $p_1(x_1,x_2,x_3,\ldots)$ and $p_o(x_1,x_2,x_3,\ldots)$, similar to $p_o(x)$ and $p_1(x)$. The joint likelihood ratio is then

$$L(x_1,x_2,x_3,\ldots) \triangleq \frac{p_1(x_1,x_2,x_3,\ldots)}{p_o(x_1,x_2,x_3,\ldots)} .$$

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If the observations $(x_1,x_2,x_3,\ldots)$ can be considered statistically independent, then the appropriate multi-dimensional probability density function can be described as the product of the individual probability density functions, thus

$$L(x_1,x_2,x_3,\ldots) = \frac{p_1(x_1) \cdot p_1(x_2) \cdot p_1(x_3) \ldots}{p_o(x_1) \cdot p_o(x_2) \cdot p_o(x_3) \ldots} .$$

This yields a significant simplification in the determination of processor output statistics, and leads to the suggestion of the log likelihood ratio, $\ell(x_i)$, which is formed by taking the logarithm of $L(x_i)$, thus

$$\ell(x_i) \triangleq \text{Log}\left[L(x_i)\right] = \text{Log}\left[\frac{p_1(x_i)}{p_o(x_i)}\right] ,$$

$$\ell(x_i) = \text{Log}\left[p_1(x_i)\right] - \text{Log}\left[p_o(x_i)\right] , \quad \textit{and}$$

$$\ell(x_1,x_2,x_3,\ldots) = \ell(x_1) + \ell(x_2) + \ell(x_3) + \ldots \quad .$$

The procedure of adding rather than multiplying lends itself quite well to a digital computer, however, the process of taking a logarithm can be time consuming. Consequently, a linear approximation to the log likelihood ratio has been implemented. This approximation is described in Appendix B of reference 1.

A.1.3 Sequential Testing

It is of interest to next consider a system in which the number of observations is not a fixed quantity but, instead, a decision is to be made when specified confidence levels are reached. This technique is known as sequential testing, and requires the establishment of two thresholds, T_o and T_1. In the SLR case at hand, the threshold T_o, with $(\underline{x}) = (x_i, x_{i+1}, \ldots, x_{j-1}, x_j)$, is chosen such that if the value of the log likelihood ratio, $\ell(\underline{x})$, falls below T_o, the decision is made that H_o is true, that no target is present. Thus the track is rejected as noise, and the testing chain stops.

Similarly, T_1 is chosen such that if $\ell(\underline{x})$ exceeds T_1, the decision is made that H_1 is true, that a target is present. This completes the detection process in a sense, but the testing procedure does not stop. Rather, the sequential testing continues and forms an automatic track. If the value of $\ell(\underline{x})$ lies between the thresholds, that is, if

$$T_o < \ell(\underline{x}) < T_1$$

no decision is made. Instead, another sample is taken, $\ell(\underline{x})$ is updated, and the new $\ell(\underline{x})$ is compared with T_o and T_1.

This process is very similar to the random walk problem, and it can be shown that eventually, with probability 1, one of the two thresholds will be crossed and a decision will be reached. The average number of samples required to reach a decision for given probabilities of wrong decisions for the sequential test described above, is less than the number required for a fixed sample-size test with the same probabilities of wrong decisions. If the track is noise, the decision is reached relatively promptly, but if the track is a target, a significantly greater number of samples may be required for a decision[5].

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The sequential testing of hypotheses is described in more detail in Appendix A of reference 1, where expressions for T_o and T_1 are derived.

A.1.4 Tracking With the SLR Procedure

In sonar applications one difficulty arises which does not often occur in other statistical decision theory applications. This problem is that one does not really know uniquely how to make a single "next" observation. For example, receipt of a modestly large sample on one beam, at a given range and perhaps with some Doppler, gives an indication of approximately where to look in the next echo cycle, in terms of beam, range, and Doppler. This information, however, cannot give a precise specification of the location of the linking sample in the next echo cycle. Thus, the process is more complex than the classical sequential test which is conducted in a single resolution cell. The information gained from the received sample thus defines a volume in the next echo cycle which must be scanned, the volume being defined usually by a range interval and a beam interval. This volume must be searched to determine whether any linkages exist with the previous data.

Since multiple linkages are allowed in this process, the definition of the joint likelihood ratio must be altered slightly. The joint likelihood ratio for the case in which multiple linkages are allowed can now be defined as

$$L'(\underline{x}) \triangleq \frac{p_1(\underline{x} \mid H_1)P_1}{p_o(\underline{x} \mid H_o)P_o} \ ,$$

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where $p_i(\underline{x} \mid H_i)$ is the conditional probability density function of $\underline{x}$ given that hypothesis H_i is true. P_1 is the probability that a linkage formed is really a target, given that H_1 is true*; and P_o is the probability that the linkage formed is really noise, given that H_o is true.

For the purpose of this analysis, it is assumed that P_o is exactly one. It is also assumed that P_1 is the number of true target tracks within the linkage volume divided by the number of possible linkages, including target and noise linkages. It is unlikely that there will be more than one true target track in any given volume when H_1 is chosen, so the average number of target tracks there is 1.0. Since it would be difficult and time consuming to count the number of possible linkages each time, the average number of possible linkages, N, will be used, hence

$$P_o = 1.0, \text{ and}$$

$$P_1 = \frac{1.0}{N} .$$

Thus the likelihood ratio $L(\underline{x})$ must be divided by the average number of possible linkages under hypothesis H_1. That is,

*If multiple linkages are allowed, there is a probability that a true target track can link with a noise sample, as well as a target sample, consequently the joint likelihood ratio must be modified by P_1.

$$L'(\underline{x}) = \frac{L(\underline{x})}{N} , \quad \text{and}$$

$$\ell'(\underline{x}) = \ell(\underline{x}) - \text{Log}\ (N) \ .$$

This reduction of the likelihood ratio due to the allowance of multiple linkages implies that it is advantageous to form a highly localized target track. If it is possible by some means to confine the volume of legitimate linkages to a relatively modest volume, then the quantity (N) may be decreased, and the average number of samples required to make a decision when a target is indeed present may be decreased.

A.2 DESCRIPTION OF THE SLR COMPUTER PROCESS

A.2.1 Introduction

This section of Appendix A describes the computer process designed to accomplish SLR processing on output data from a single ping sonar signal processor. This computer process is implemented on a UNIVAC 1108 digital computer. The characteristics of this particular implementation are such that the process may be implemented on a reasonably modest, state-of-the-art digital computer, such as can be found on board newer surface ships.

The overall purpose of the SLR process is to produce a sonar display with reduced clutter, wherein the computer can perform ping-to-ping integration for any echo returns not large enough to display initially. In this manner, the sonar operator

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may remain alerted for longer periods of time, as well as becoming alerted earlier than with only the conventional processor. This process has been designed as a function which can be inserted into a conventional active sonar processing system between the output of the signal processor and the cathode ray tube (CRT) display. The primary requirement for its implementation is a digital computer with sufficient capacity. Specific requirements will be discussed later in this appendix.

The information flow in the SLR computer process is shown in Fig. A-2. The remainder of this section is devoted to a more detailed explanation of the process.

A.2.2 Preliminary Data Reduction

For the purpose of this explanation it is assumed that the output of the sonar signal processor is time-normalized. Thus the normalized data from the current ping cycle are processed first by the Preliminary Data Reduction section. This section has three purposes. First, the data received are grouped into single ping event packages and, if necessary, are converted from analog to digital format. These single ping event packages contain information such as the range, bearing and amplitude of each data point. In order to facilitate digital computer processing with the SLR method, the parameters which describe a single ping event package are divided into resolution cells, each corresponding to an incremental range of the parameter of interest. For example, a mark on the display may represent 50 yards, hence a suitable definition of a range resolution cell. These resolution cells may be adjusted to comply with both the sonar system and the computer available.

Second, the section performs a preliminary thresholding function. The threshold used here is not the lower decision threshold used in the sequential test but is a threshold set low enough that any information of interest may pass, yet high enough to allow

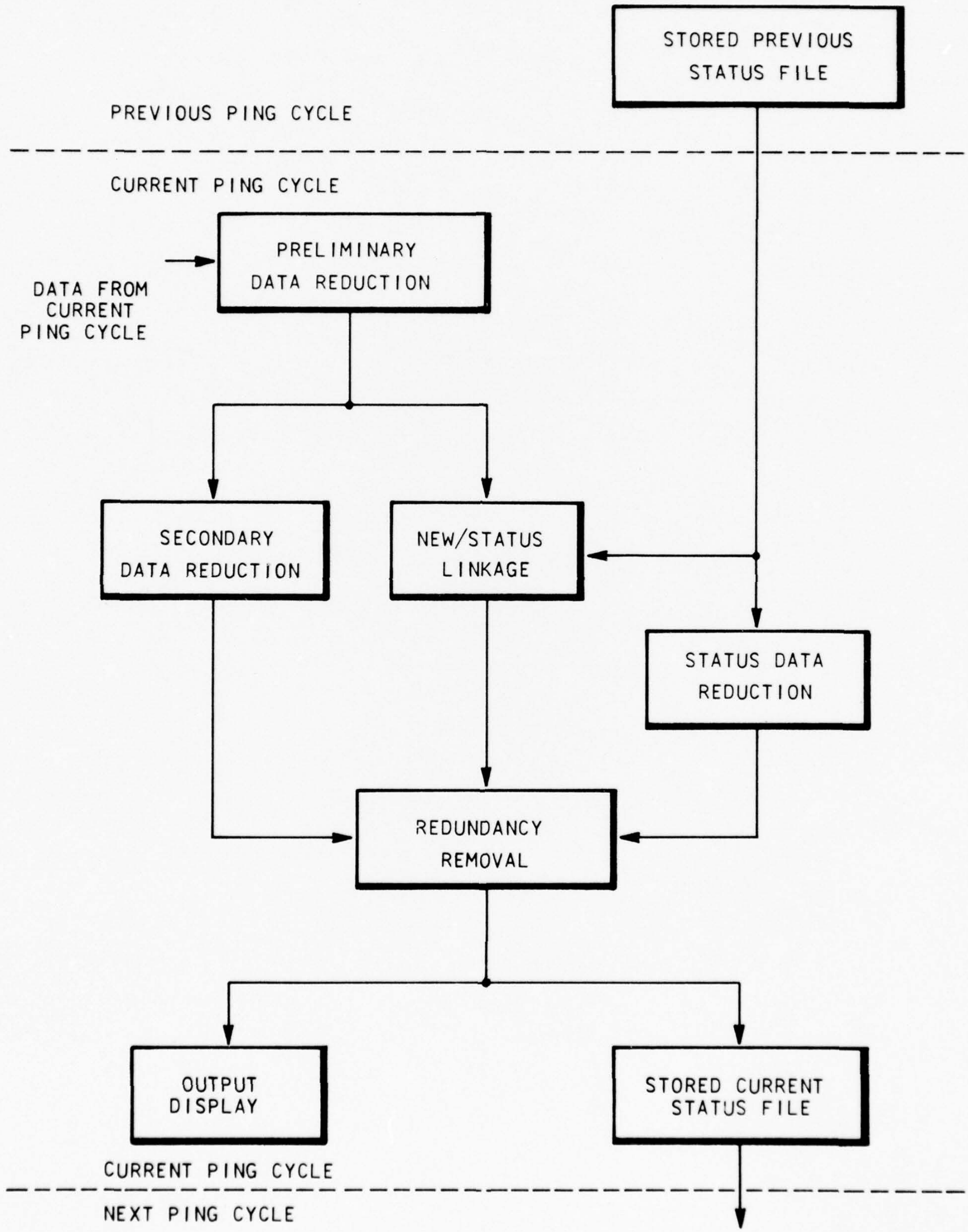

FIG. A-2 GENERAL DATA FLOW IN THE SLR PROCESS

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reduction of the data passed to the remainder of the SLR process by 90 to 99%. It is intended that a trained operator have control over this threshold. Third, the amplitude of each data point which passed the preliminary threshold is mapped to the logarithm of its likelihood ratio, using the linear approximation developed in Appendix B of reference 1. This specific transformation is dependent upon the particular sonar signal processor being used, as explained previously. Though the exact transformation equations are often quite complex, in every case considered the transformation can be accurately represented by a linear equation of the form

$$\ell(x_i) = A + B \cdot x_i \ ,$$

where A and B are constants such as those derived in Appendix B of reference 1. The output of the Preliminary Data Reduction section is passed to two sections, New/Status Linkage, and Secondary Data Reduction.

A.2.3 New/Status Linkage

The New/Status Linkage section receives two inputs; one is the reduced single ping sonar output from the Preliminary Data Reduction section, and the other is the series of multiping event packages from the previous ping status file, each event package being one status unit.

A.2.3.1 Status file. Each event package, or status unit stored in the status file is represented by four functional quantities which are listed below:

1. The event position vector from the preceding echo cycle;
2. The expected event position vector for the current echo cycle;

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3. The volume variance vector for the current echo cycle; and
4. The joint log likelihood ratio resulting from the previous echo cycles.

The number of dimensions required for the three vectors depends upon the sonar system. That is, the number of dimensions depends upon the number of meaningful quantities that can be measured for each peak by the sonar system. The variance vector defines the volume centered about the expected position vector within which legitimate linkages can occur during the current echo cycle with the event logged in the status unit.

A.2.3.2 Linkage process. The New/Status Linkage section compares each status unit with the single ping event packages from the reduced sonar output. If the single ping event position vector lies within the volume variance of the status unit, the single ping event is said to be linked with the status file entry. When this situation occurs, the joint log likelihood ratio of the new multiping event is formed by the process described earlier in this appendix and is then tested against the lower decision threshold, T_0.

If this new joint log likelihood ratio is greater than T_0, then a new status unit is formed, with information from the old status unit being processed in conjunction with the single ping event package to generate a new event position vector, a new estimated position vector, and a new volume variance vector for the new status unit. If the new joint log likelihood ratio is less than T_0, then hypothesis H_0 is chosen and the track linkage is discarded, precluding the calculation of a new status unit.

A status unit is allowed to link with all events which fall within its variance volume of suspicion. Similarly, a single ping event can fall within the variance volumes of several status

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units and hence be linked several ways. This procedure allows many incorrect linkages, but since all incorrect linkages will yield a noise track, the process will decrease the log likelihood ratio and the track will eventually be dropped. The process will reach a steady-state condition in which as many noise tracks are being discarded as are being added, on the average.

A.2.4 Secondary Data Reduction

The reduced sonar output from the Preliminary Data Reduction section is also processed by the Secondary Data Reduction section. The Secondary Data Reduction section tests the log likelihood ratio of the single ping event package against the lower decision threshold, T_0, and makes the appropriate decision. If indeed the single ping event exceeds the threshold, a new status unit is created on a single ping basis, except that the volume variance vector is larger than for most multiping status units, since there is not as much information regarding an expected position vector in the sense of a multiping status unit.

Upon initialization of the SLR computer process, there are no previously acquired status units, hence the Secondary Data Reduction section is the only section capable of producing a status unit. In each echo cycle, it is here that new tracks are started. Note that the entire process does not preclude a single large echo return being entered into the status file and being placed upon the output display immediately.

A.2.5 Status Data Reduction

The status file information is utilized in two ways in the SLR computer process. As described above, each status unit is furnished to the New/Status Linkage section to determine linkages and form target tracks. Also, the entire status file is passed through the Status Data Reduction section. The purpose

of this section is to maintain a strong target track even though the current echo cycle did not produce a linkage with this track.

This function is accomplished by assuming that each status unit linked with a small single ping event whose log likelihood ratio was just below T_o, and whose position vector was the same as the expected position vector of the status unit being processed. The volume variance vector is enlarged to accommodate the increased uncertainty of target position, and a possible new status unit is formed. The log likelihood ratio of the new status unit is tested against T_o, and the appropriate decision is made. If the new status unit exceeds the threshold, it is passed to the next processing section. This procedure helps to avoid losing a well-established track because of a single miss, yet a noise track is discarded quickly because of the degradation.

A.2.6 Redundancy Removal

From the above discussion, it is seen that there are three sections in the SLR process capable of producing status units to be entered into the current status file. The three sections are listed below:

1. New/Status Linkage;
2. Secondary Data Reduction; and
3. Status Data Reduction.

Since these three sections operate independently in generating possible status units, there is a possibility that some of the status units will be redundant, that is, several may have the same predicted location vector and the same present location vector, in terms of resolution cells. This redundancy can be caused in a number of ways. For example, a single ping entry may be formed, a linkage also formed with the single ping entry, and a track propagation entry may be formed, all with the same

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present and expected position vectors. The redundancy removal section scans all entries to determine these redundancies and removes all except the status unit with the largest log likelihood ratio.

The output of the Redundancy Removal section is the new status file for the current echo cycle. This is placed in storage for the next echo cycle, and is made available to the Output Display.

A.2.7 Output Display

The Output Display section is assumed to be part of the original sonar system. Hence, the operator should have control of the display threshold, T_1. By increasing this threshold, the operator can reduce the clutter to a more acceptable rate with the SLR and retain the same information as without the SLR processor. When the operator becomes alerted, he can lower the display threshold in order to look at the status file in more detail, since a change in the display threshold immediately changes what information is displayed. There is no need to wait for past events to accumulate on the display, since the accumulation has already occurred and is stored in the status file.

Note that the SLR process does not include a fundamental specification of the number of echo cycles over which integration will be carried. Rather, a single status unit could represent a track that has been carried for an indefinite number of pings. Note also that a change in the lower decision threshold does not affect the degree of clutter on the display, but only the amount of processing and storage. Hence there is significant improvement over conventional approaches which allow ping-to-ping integration only through the operator looking at the display, in which it is necessary to operate with a clutter rate sufficient to allow small echoes to mark the display so that the ping-to-ping integration process may begin.

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APPENDIX B

COMPUTER REQUIREMENTS FOR THE SLR PROCESS

B.1 INTRODUCTION

The primary consideration involved in actually implementing the SLR processing method for shipboard usage is the computer capacity available. This capacity includes both speed of execution and available storage. The requirements for each of these items are determined to a large extent both by design parameters of the sonar and by the statistical characteristics of the SLR process. This appendix lists the pertinent parameters and relates them to actual storage and operation time values.

B.2 SLR PROCESS DESIGN PARAMETERS

The basic design parameters for the SLR process include those listed below:

1. The *output statistics* of the sonar signal processor for noise and signal-plus-noise into the processor, including the output bandwidth of the processor;

2. The time between pings;

3. The number of dimensions of a target track which the sonar is capable of measuring, including range, bearing, etc.;

4. The number and size of resolution cells desired in each dimension;

5. The dynamic constraints on the rate of change of each dimension;

6. The desired display clutter rate; and

7. The minimum signal-to-noise ratio of interest.

These design parameters may be separated into two categories, sonar parameters and SLR decision parameters. This is discussed below.

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B.2.1 Sonar Parameters

The SLR procedure is a statistical test, consequently the statistical representation of the input to the SLR processor is the most important factor in determining the necessary computer capacity. Thus the output statistics of the sonar signal processor must be known under all desired operating conditions. Conditions of noise alone and signal-plus-noise for the entire range of application must be known in order to calculate both the likelihood ratio and probabilities associated with the continuance or termination of the sequential test. It is desirable to have these statistical representations in closed form, however, the required relationships can be derived from a tabulated function with the aid of a digital computer.

The output bandwidth of the sonar signal processor is important in several ways. The most significant role of the output bandwidth is the determination of the rate at which independent samples are produced by the sonar processor. This rate, in turn, is related to the number of samples to be allowed for each range resolution cell. The time between pings is very important, since the SLR process must complete its operation for each ping cycle before the next ping cycle begins.

B.2.2 SLR Decision and Tracking Parameters

The most important SLR decision and tracking parameter is the total number of resolution cells desired. This total number, the product of the number of resolution cells in each dimension, determines largely the computer storage necessary for the SLR process.

Another important parameter that affects computer loading is the maximum rate of change allowed for a target's motion in each dimension. This parameter determines the allowable size of the volume variance vector, and consequently the

number of independent samples with which a status unit may be linked. The present implementation includes two fixed variances: a large one associated with single events, which allows a linkage on the next ping for a target with a reasonable opening or closing range rate, and a smaller one associated with an established track, which allows for variations in the observed range rate.

The major objective of the SLR process is to obtain a high probability of detection, along with a reduced clutter rate. The clutter rate is closely related to the output statistics of the sonar processor, since the clutter rate is affected by both the design S/N used in determining the log likelihood ratio transformation, and the probabilities associated with terminating and continuing the SLR test.

In order to obtain the design S/N for a specified minimum detectable S/N, the design S/N should be chosen such that a sample of the minimum detectable S/N will be assigned a log likelihood ratio of zero, on the average. Under this condition there will be an average probability of detection of 0.5 for a target with this minimum detectable S/N. For a more detailed discussion of this see Appendix B of reference 1. The design S/N closely affects the number of noise samples which may result in a choice of hypothesis H_1, and hence the clutter rate.

B.3 AVERAGE NUMBER OF STATUS UNITS REQUIRED

The objective of this section is to derive a relationship to determine the average number of status units created in one echo cycle by the sequential testing procedure described previously. It is assumed that the test has been operating in a noise-only environment long enough to reach a steady state condition; that is, as many status units are being created as discarded. The assumption of noise alone is not unreasonable,

since a true target track would create only one status unit and possibly a few status units describing branching noise tracks.

Knowledge of the sonar processor output statistics allows the calculation of P_1, the probability of an independent sample of the sonar processor exceeding a threshold T similar to that utilized in the Preliminary Data Reduction section. Assuming the maximum of the N_1 independent samples within a resolution cell will be chosen, the probability that at least one independent sample within the resolution cell will exceed the threshold T is given by

$$P_T = 1 - (1 - P_1)^{N_1} .$$

Recall that the total number of resolution cells, N_R, is given by the product of the number of resolution cells in each dimension.

As described in Appendix A of this report, status units may be produced three ways. For the purposes of this calculation, it will be assumed that the Status Data Reduction section of the process creates a negligible number of status units. This section is primarily utilized to propagate strong target tracks which perhaps have not linked within the present ping cycle, consequently, the noise-only assumption will be used.

The probable number of status units created or continued in a single echo cycle will now be calculated. Two sources may be considered: the Secondary Data Reduction section and the New/Status Linkage section. The status units obtained from the New/Status Linkage section will be separated into two categories: first, those arising from the linkage of an input sample with an established status unit representing a single

ping event; and second, those arising from the linkage of an input sample with an established status unit which represents a multiping track, having linked at least twice beforehand.

B.3.1 Status Units From Secondary Data Reduction

For any sample x_i taken from a resolution cell a likelihood ratio is formed by the relationship

$$L(x_i) = \frac{p_1(x_i)}{p_o(x_i)} ,$$

where $p_1(x)$ is the probability density function describing signal-plus-noise, and $p_o(x)$ is the probability density function describing noise alone. If $L(x_i)$ is greater than T_o, the lower decision threshold, then a status unit will be formed by the Secondary Data Reduction section. P_1, the probability that the status unit will be formed, is given by the relationship

$$P_1 = 1 - \{1 - P[L(x_i) > T_o]\}^{N_1} .$$

The probability that a status unit will not be formed here is then $1 - P_1$; thus N_1, the number of status units formed in the Secondary Data Reduction section is a binomially-distributed random variable with mean $\overline{N_1}$, given by

$$\overline{N_1} = N_R \cdot P_1 ,$$

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and standard deviation σ_{N_1}, given by

$$\sigma_{N_1} = \sqrt{N_R \cdot P_1 \cdot (1 - P_1)} \quad .$$

B.3.2 Status Units From New/Status Linkage

The contribution of the first set of linkages from the New/Status Linkage section to the average number of status units created in one echo cycle will now be calculated. The first type linkages are those which arise from the linkage of an input sample with a status unit which represents a single ping event. That is, the single ping status unit was formed during the preceding echo cycle by the Secondary Data Reduction section. P_2, the probability that $L(\underline{x})$ will exceed T_o, is given by

$$P_2 = P[L(\underline{x}) > T_o | x_1 > T;\ L(x_1) > T_o;\ x_2 > T] \ ,$$

or

$$P_2 = \frac{P[L(\underline{x}) > T_o;\ x_1 > T;\ L(x_1) > T_o;\ x_2 > T]}{P_1 \cdot P_T^2} \ ,$$

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where

$(\underline{x}) = (x_1, x_2)$;

x_1 = the amplitude of the peak giving rise to the single-ping status unit;

x_2 = the amplitude of the input sample being considered; and

N_L = the average number of status units in a large volume variance.

The number of the first type of status units, N_2, is also a random variable, with mean $\overline{N_2}$ given by

$$\overline{N_2} = \overline{N_1} \cdot (N_L \cdot P_T) \cdot P_2 ,$$

with standard deviation σ_{N_2} given by

$$\sigma_{N_2} = \sqrt{N_1 \cdot (N_L \cdot P_T) \cdot P_2(1 - P_2)} \quad .$$

The contribution of the second type of linkages to the average number of status units created in one echo cycle will now be calculated. The second type of linkages are those which arise from an input sample linking with an established status unit which represents a multiping event, having linked at least twice beforehand. In order to calculate this contribution, it is necessary to find the average number of samples necessary to reject a track as noise, known as the average sample number (ASN).

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The direct calculation of this number is quite complex, however, certain approximations found in Wald[4] allow a somewhat simpler procedure.

The average sample number (ASN) may be found using the probability density function describing the thresholded output of the sonar processor with noise alone input to the processor. The function $f_o(x)$ is given by

$$f_o(x) = \dot{P}(x) = \frac{d}{dX} P(x < X \mid T < x)$$

$$f_o(x) = \frac{d}{dX} \frac{P(T < x < X)}{P(T < x)}$$

$$f_o(x) \begin{cases} = \dfrac{p(x)}{P(T < x)} & T < x \\ = 0 & \text{otherwise,} \end{cases}$$

where $p(x) = \frac{d}{dX} P(x < X)$.

Formally, the average sample number is given by

$$\text{ASN} = \sum_{i=1}^{\infty} i \cdot P_i \ ,$$

where P_i is the probability that the test will end on the i^{th} sample. If ASN′ is the average sample number for tests which have been carried on for at least two samples, then the ASN may be approximated by the relationship

$$ASN = \frac{P_1 P_2}{P_T} \cdot ASN' + (1) \cdot (1 - \frac{P_1}{P_T}) + (2) \cdot (\frac{P_1}{P_T}) \cdot (1 - P_2) \ .$$

Solving for ASN′ yields

$$ASN' = (ASN - 1 - \frac{P_1}{P_T}) \cdot (\frac{P_T}{P_1 \cdot P_2}) + 2 \ .$$

By simulating the sequential testing procedure on a digital computer, it is possible to calculate an estimate of the standard deviation of ASN′, $\hat{\sigma}_{ASN'}$. The results show that $\hat{\sigma}_{ASN'}$ is about 0.5 when ASN′ is in the range, $3 < ASN' < 4$.

The average number of linkages formed from an input sample linking with a multiping event can now be expressed as

$$\overline{N_3} = \overline{N_2} \cdot (N_S \cdot P_T) \cdot (ASN' - 2) \ ,$$

where N_S is the number of resolution cells in the small volume variance. The probability density function of ASN′ is not known; hence the standard deviation of N_3 cannot be formed. It is reasonable, however, to provide an estimate of the standard deviation of N_3, $\hat{\sigma}_{N_3}$, by proceeding in the same fashion as for σ_{N_1} and σ_{N_2}, hence

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$$\hat{\sigma}_{N_3} = \sqrt{(N_2) \cdot (N_S \cdot P_T) \cdot \hat{\sigma}^2_{ASN}}\ .$$

If N_R and $N_R N_L P_T^2$ are each large, the binomial distributions may be approximated by Gaussian distributions with the given means and standard deviations. Thus the estimate of the average total number of status units created in each echo cycle under noise alone conditions is

$$\overline{N}_{total} = \overline{N}_1 + \overline{N}_2 + \overline{N}_3\ ,$$

with standard deviation given by

$$\sigma_{N_{total}} = \sqrt{\sigma^2_{N_1} + \sigma^2_{N_2} + \hat{\sigma}^2_{N_3}}\ .$$

B.4 ACTUAL DATA STORAGE REQUIREMENTS

The average total number of status units required may now be used to determine the actual data storage requirements for the SLR processor. It is now necessary to find the number of computer words required to describe each status unit, which contains a position vector from the preceding echo cycle, the expected position vector for the current echo cycle, a volume variance vector, and the joint log likelihood ratio for the event.

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A position vector as implemented includes range and bearing. If 2048 or less range resolution cells are allowed, then 11 bits will describe the range. If 16 bearing cells are allowed, then 4 bits will suffice to describe sample bearing. Thus the position vector together with the expected position vector will require 2(11 + 4) = 30 bits. The variance vector can be keyed with an indicator to determine which of a stored set of variance vectors applies, thus an indicator of 3 bits is sufficient. The likelihood ratio can be represented by a scaled 12-bit integer, giving 3 significant decimal digits. Thus for the multibeam case described above, a total of 45 bits of information is required for each status unit. This information could be packed in several computer words, depending upon the length of word available.

B.5 AVERAGE NUMBER OF COMPUTER INSTRUCTIONS REQUIRED

Once the storage requirements of the SLR process have been tailored to fit that available, the expected execution time must be considered. The execution time depends upon the number of computer instructions to be carried out during an echo cycle, which in turn is related to the number of status units being created. To find the total average number of computer instructions required, the processing cycle will be considered in three parts: the Secondary Data Reduction, the New/Status Linkage, and the Status Data Reduction sections. The number of instructions will vary depending upon the actual computer utilized, since the number of instructions available varies. The numbers quoted here are based upon the machine language listing of the SLR program written in UNIVAC FORTRAN V. Here, speed and storage were sacrificed where necessary to obtain flexibility. Careful machine language programming for a specified application could reduce the number of required instructions.

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Each single ping event which enters the Secondary Data Reduction section requires I_1 instructions, given by

$$I_1 = I_1' + \left(\frac{P_1}{P_T}\right) I_1'' ,$$

where

I_1' = the number of instructions required to determine whether the single ping event should form a status unit; and

I_1'' = the number of instructions necessary to form a status unit.

For the present program,

$$I_1 = 9 + \left(\frac{P_1}{P_T}\right)(22) .$$

Each sample which enters the New/Status Linkage section from the Preliminary Data Reduction section requires I_2 instructions, given by

$$I_2 = (I_2') + \frac{2N_L\overline{N}_{total}}{N_R}(I_2'') + \frac{\overline{N}_2 + \overline{N}_3}{N_R P_T}(I_2''')$$

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where

I_2' = the number of instructions required initially to process each new sample;

I_2'' = the number of instructions required to consider linkages; and

I_2''' = the number of instructions necessary to form a status unit.

For the present program,

$$I_2 = 38 + \frac{2N_L\overline{N}_{total}}{N_R}(29) + \frac{\overline{N}_2 + \overline{N}_3}{N_R P_T}(80) \ .$$

The number of instructions required for the Status Data Reduction section is I_3, given by

$$I_3 = \overline{N}_{total} \cdot I_3' \ ,$$

where

I_3' = the number of instructions necessary to consider whether to propagate an established track.

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For the present program,

$$I_3 = \overline{N}_{total} \cdot 73 \ .$$

Since the total number of input samples from the Preliminary Data Reduction section is $N_S = N_R P_T$, the total number of instructions to be expected for each ping cycle is I_{total}, given by

$$I_{total} = N_R P_T (I_1 + I_2) + I_3 \ .$$

If T_I is the execution time of a computer instruction, the total execution time, T_{total}, is

$$T_{total} = T_I \cdot I_{total} \ .$$

Thus expressions have been derived which allow the calculation of necessary computer storage and execution time in terms of the design parameters of the SLR process.

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APPENDIX C
DISPLAY SIMULATION FACILITY

C.1 TELEVISION DISPLAY SYSTEM

The CRT display unit used to compare the two processing methods is a digital television system. A functional diagram of the system is shown in Fig. C-1. The system will accept digital data, generated by the UNIVAC 1108 computer, from a digital magnetic tape. The control unit is programmable, providing a wide variety of formats for the display of information. The display can consist of eight levels of grey, ranging from black to bright white, or the display may be in color, where there are 512 different colors available. The active screen area is square, and covers over 110 square inches, with over 40,000 available independent data spots. There are up to 64 alphanumeric characters available for display on the screen.

The display is dynamic, that is, the information displayed might be continuously varied in time. A very important application of this feature has been the simulation of many different types of sonar displays, including both operational and proposed sonars. In this simulation, bearing, range, amplitude, and/or time information from active or passive sonars can be presented to an operator just as if he were on board ship. There is an anechoic acoustical isolation booth available for the operator, with separate controls so that he may also initiate ping cycles or stop the input of new information, providing a static, flicker-free display. With the isolation booth, studies may also be performed with a combination of audio and visual information, providing the capability to simulate operator environment, existing or theoretical.

Existing sonar displays which have been simulated include the AN/SQS-26 (A-scan and B-scan), the AN/SQQ-23 PAIR, and the AN/BQR2-DIMUS displays. The effects of mutual ship interference were studied effectively with a realistic sonar environment for the

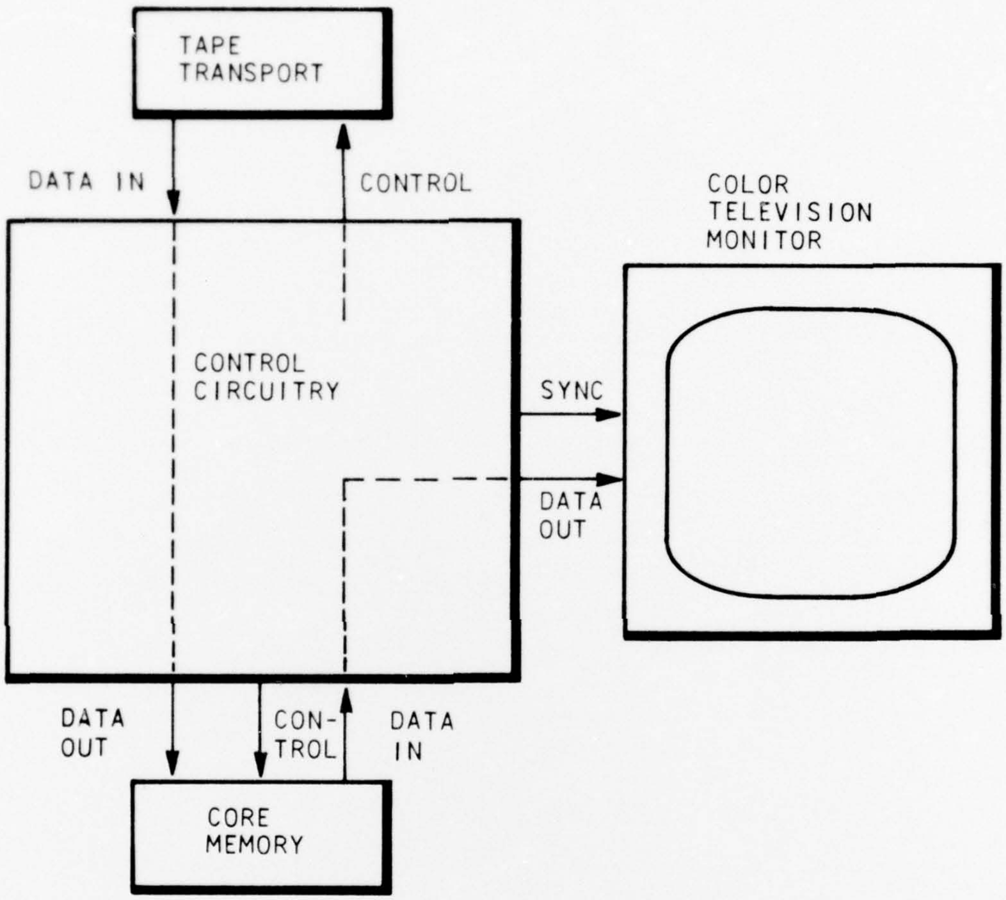

FIG. C-1 BASIC DISPLAY SYSTEM BLOCK DIAGRAM

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active sonars. Studies have been made to determine optimum pulse shapes for detection and classification of underwater targets. Much exploratory development has been performed concerning the use of color displays in future sonar systems, utilizing colors to represent such quantities as Doppler shifts, amplitude, and bearing angles. The simulated displays have also been used in a series of psychophysical experiments to determine the effect of information presentation technique on human observers. Through this human factor research, the present understanding of the man-machine interface may be greatly increased.

C.2 DESCRIPTION OF DIGITAL DISPLAY SYSTEM

This digital display system was designed to obtain flexible displays of information in widely varied formats. The display facility consists of four standard black and white television monitors, a color television monitor, and two smaller monitors, color and black and white, fed by a core memory through a digital control system. The core memory is updated by a digital tape transport as shown in Fig. C-1.

The general operation of the system is as follows:

(1) Magnetic tapes are generated using the computer facility. These tapes contain digital information and can represent any encoded analog signals.

(2) The digital tape transport is then used to transfer information from the magnetic tape to the core memory.

(3) The system control unit sequentially scans the core memory and transfers the information to the television display monitors. This is done at an equivalent 60 Hz rate so that a flicker free display is obtained. A 30 Hz rate can be selected to simulate some existing sonar displays in which flicker is present.

(4) New information from the digital tape input can be supplied to the core memory at any time, allowing real time changes in displayed information. The display output is completely determined by the computer program, making the display very flexible.

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13. ABSTRACT

A technique has been developed to accomplish computer-aided detection and classification of active sonar signals. The technique is based on the theory of sequential hypothesis testing and allows a digital computer to reduce the volume of input data, perform ping-to-ping integration, and present the operator with a meaningful display at a reduced clutter rate compared to typical operational displays. The necessary logical and arithmetic operations are simple and allow real-time implementation of the technique on a modest state-of-the art computer. Detailed expressions are derived which describe the relationships between computer loading and application of the computer aided technique. A method of adaptively varying the input threshold is discussed and is shown to significantly reduce computer requirements without degrading performance appreciably. A comparison of simulated displays driven with a conventional signal processor and the computer-aided technique shows that the computer-aided technique provides consistently brighter target tracks than the conventional processor with equal clutter densities.

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14. KEY WORDS	LINK A ROLE	LINK A WT	LINK B ROLE	LINK B WT	LINK C ROLE	LINK C WT
Computer-Aided Detection						
Sonar (Active)						
Sequential Hypothesis Testing						
Threshold						
Likelihood Ratio						
Simulation (Digital)						

INSTRUCTIONS

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